U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science Directorate
Geologic Resources Division

Boston Harbor Islands National Recreation Area

GRI Ancillary Map Information Document

Produced to accompany the Geologic Resources Inventory (GRI) Digital Geologic Data for Boston Harbor Islands National Recreation Area

boha_geology.pdf

Version: 1/11/2016

Geologic Resources Inventory Map Document for Boston Harbor Islands National Recreation Area

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Geologic Resources Inventory Map Document

Boston Harbor Islands National Recreation Area

Document to Accompany Digital Geologic-GIS Data

boha_geology.pdf

Version: 1/11/2016

This document has been developed to accompany the digital geologic-GIS data developed by the Geologic Resources Inventory (GRI) program for Boston Harbor Islands National Recreation Area (BOHA)
Attempts have been made to reproduce all aspects of the original source products, including the geologic units and their descriptions, geologic cross sections, the geologic report, references and all other pertinent images and information contained in the original publication.

National Park Service (NPS) Geologic Resources Inventory (GRI) Program staff have assembled the digital geologic-GIS data that accompanies this document.

For information about the status of GRI digital geologic-GIS data for a park contact:

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About the NPS Geologic Resources Inventory Program

Background

Recognizing the interrelationships between the physical (geology, air, and water) and biological (plants and animals) components of the Earth is vital to understanding, managing, and protecting natural resources. The Geologic Resources Inventory (GRI) helps make this connection by providing information on the role of geology and geologic resource management in parks.

Geologic resources for management consideration include both the processes that act upon the Earth and the features formed as a result of these processes. Geologic processes include: erosion and sedimentation; seismic, volcanic, and geothermal activity; glaciation, rockfalls, landslides, and shoreline change. Geologic features include mountains, canyons, natural arches and bridges, minerals, rocks, fossils, cave and karst systems, beaches, dunes, glaciers, volcanoes, and faults.

The Geologic Resources Inventory aims to raise awareness of geology and the role it plays in the environment, and to provide natural resource managers and staff, park planners, interpreters, researchers, and other NPS personnel with information that can help them make informed management decisions.

The GRI team, working closely with the Colorado State University (CSU) Department of Geosciences and a variety of other partners, provides more than 270 parks with a geologic scoping meeting, digital geologic-GIS map data, and a park-specific geologic report.

Products

Scoping Meetings: These park-specific meetings bring together local geologic experts and park staff to inventory and review available geologic data and discuss geologic resource management issues. A summary document is prepared for each meeting that identifies a plan to provide digital map data for the park.

Digital Geologic Maps: Digital geologic maps reproduce all aspects of traditional paper maps, including notes, legend, and cross sections. Bedrock, surficial, and special purpose maps such as coastal or geologic hazard maps may be used by the GRI to create digital Geographic Information Systems (GIS) data and meet park needs. These digital GIS data allow geologic information to be easily viewed and analyzed in conjunction with a wide range of other resource management information data.

For detailed information regarding GIS parameters such as data attribute field definitions, attribute field codes, value definitions, and rules that govern relationships found in the data, refer to the NPS Geology-GIS Data Model document available at: http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm

Geologic Reports: Park-specific geologic reports identify geologic resource management issues as well as features and processes that are important to park ecosystems. In addition, these reports present a brief geologic history of the park and address specific properties of geologic units present in the park.

For a complete listing of Geologic Resource Inventory products and direct links to the download site visit the GRI publications webpage http://www.nature.nps.gov/geology/inventory/gre_publications.cfm

GRI geologic-GIS data is also available online at the NPS Data Store Search Application: http://irma.nps.gov/App/Reference/Search. To find GRI data for a specific park or parks select the appropriate park

(s), enter “GRI” as a Search Text term, and then select the Search Button.

For more information about the Geologic Resources Inventory Program visit the GRI webpage: http://www.nature.nps.gov/geology/inventory, or contact:

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The Geologic Resources Inventory (GRI) program is funded by the National Park Service (NPS) Inventory and Monitoring (I&M) Division.

GRI Digital Maps and Source Map Citations

The GRI digital geologic-GIS maps for Boston Harbor Islands National Recreation Area (BOHA)

GRI Digital Geomorphic Map of Boston Harbor Islands National Recreation Area, Massachusetts (*GRI MapCode BOHA*)

The map was produced using source digital data and maps from the following source,

FitzGerald, D.M., Hughes, Z.J., and Rosen, P., 2013, Surface Geomorphology Map of Boston Harbor National Recreation Area: Boston University, unpublished digital data and maps, scales 1:500 and 1:200 (*GRI Source Map ID 75746*)

Several islands within the park lacked bedrock exposure (i.e., no bedrock reported, as per the source report and data). See the Extent Index Map and Index Table listing for bedrock GIS data coverage extent.

GRI Digital Bedrock Geologic Map of of Boston Harbor Islands National Recreation Area, Massachusetts (*GRI MapCode BHBR*)

The map was produced using source digital data and maps from the following source,

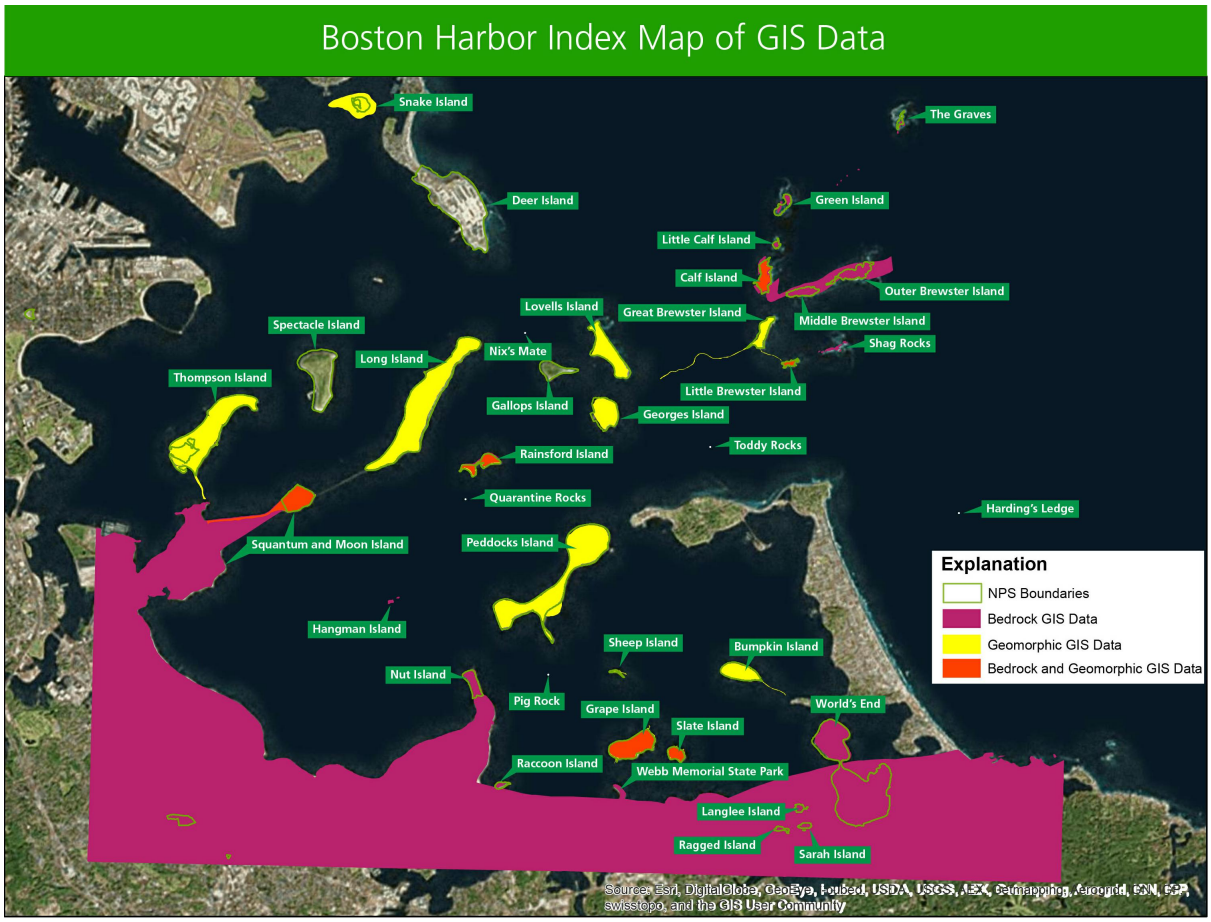
Thompson, Peter J., Kopera, Joseph P. and Solway, Daniel, 2011, A Report on the Bedrock Geology of Boston Harbor to the National Park Service: Massachusetts Geological Survey, working draft map (8-24-2011), scale 1:24,000 (*GRI Source Map ID 75578*)

Several islands within the park have no surficial mapping, the result of inaccessibility of the source maps authors to these islands (pers. comm. with Zoe Hughes, 2014). See the Extent Index Map and Index Table listing for geomorphic GIS data coverage extent.

Additional information pertaining to each source map is also presented in the Source Map Information (BOHAMAP) table included with the GRI geologic-GIS data.

Extent of GIS Data Index Map

Not every island that comprises Boston Harbor Islands National Recreation Area has geomorphic and/or bedrock geology coverage. Below is an index map showing which areas have bedrock GIS data (shown in magenta), geomorphic GIS data (shown in yellow) or both bedrock and geomorphic GIS data (shown in orange). Areas and islands not outlined in any color have no map/data coverage. For a number of park islands this is simply because no bedrock was reported (Massachusetts Geological Survey Bedrock Geology Map). However, for geomorphic coverage this was often due to inaccessibility to an island (pers. comm., 2014 with Boston University geomorphic source map authorship).



Extent of GIS Data Index Table

Islands, as well as notable landmark features, within Boston Harbor Islands National Recreation Area are listed below. For each island or notable landmark feature the presence (Yes) or absence (No) of both geomorphic GIS data and bedrock GIS data is noted.

Island Name	Geomorphic GIS Data	Bedrock GIS Data
Bumpkin Island	Yes	No
Button Island	No	Yes
Calf Island	Yes	Yes
Deer island	No	No
Gallops Island	No	No
Georges Island	Yes	No
Grape Island	Yes	Yes
The Graves	No	Yes
Great Brewster	Yes	No
Green Island	No	Yes
Hangman Island	No	Yes
Harding Ledge	No	No
Langlee Island	No	Yes

Island Name	Geomorphic GIS Data	Bedrock GIS Data
Little Brewster	Yes	Yes
Little Calf Island	No	Yes
Long Island	Yes	No
Lovells Island	Yes	No
Middle Brewster	No	Yes
Moon Island	Yes	Yes
Nixes Mate	No	No
Nut Island	No	No
Outer Brewster	No	Yes
Peddocks Island	Yes	No
Pig Rock	No	No
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
Slate Island	Yes	Yes
Snake Island	Yes	No
Spectacle Island	No	No
Sunken Ledge	No	No
Thompson Island	Yes	No
Toddy Rocks	No	No
Webb Memorial Park	No	Yes
Worlds End	No	Yes

GRI Digital Geomorphic Map of Boston Harbor Islands National Recreation Area

Geomorphic Map Unit List

The geomorphic units present on the GRI Digital Geomorphic Map of Boston Harbor Islands National Recreation Area are listed below in alphabetical unit symbol order save unit br (bedrock), the oldest unit, which is listed last. Units are listed with their assigned unit symbol and unit name (e.g., Qaf - Artificial fill). Many areas were mapped with overlapping polygons of differing unit types. These areas are denoted by concatenating all units present with a "+" in between each unit (e.g., Qds+Qsa indicates an area that was mapped as both Qds (Dune system) and Qsa (Salient)). All units, as well as unit combination areas, are listed below. Information about each geologic unit is also presented in this dataset's Geologic Unit Information (BOHAUNIT) table included with the GRI geomorphic-GIS data. Links exist to individual unit type descriptions.

Cenozoic Era

Quaternary Period

Qaf - Artificial fill
Qdr - Drumlin
Qds - Dune system
Qds+Qsa - Dune system and salient
Qds+Qsa+Qsp+Qwb - Dune system, salient, spit and welded bar
Qds+Qsp+Qwb - Dune system, spit and welded bar
Qgfd - Glacio-fluvial deposits
Qgr+Qot+Qwb - Gravel ridge, overwash terrace and welded bar
Qgr+Qsa+Qsp+Qwb - Gravel ridge, salient, spit and welded bar
Qgr+Qwb - Gravel ridge and welded bar
Qi - Inlet
Qib - Intertidal bar
Qk - Kettle
Qla - Lagoon
Qla+Qt+Qwb - Lagoon, tombolo and welded bar
Qla+Qwe - Lagoon and wetland
Qmp - Marsh pond
Qmrt+Qsa+Qwb - Marine-reworked till, salient and welded bar
Qmrt+Qwb - Marine-reworked till and welded bar
Qot - Overwash terrace
Qot+Qsa - Overwash terrace and salient
Qot+Qsa+Qwe - Overwash terrace, salient and wetland
Qot+Qsp+Qwb - Overwash terrace, spit and welded bar
Qot+Qt+Qwb - Overwash terrace, tombolo and welded bar
Qot+Qwe - Overwash terrace and wetland
Qsa - Salient
Qsa+Qsp+Qwb - Salient, spit and welded bar
Qsa+Qwe - Salient and wetland
Qsp - Spit
Qsp+Qwb+Qwe - Spit, welded bar and wetland
Qsp+Qwb - Spit and welded bar
Qt+Qtc+Qwb - Tombolo, tidal channel and welded bar
Qt+Qwb - Tombolo and welded bar
Qt+Qwb+Qwe - Tombolo, welded bar and wetland

Qtc - Tidal channels
Qtcb - Till-covered bedrock
Qtf - Tidal flat
Qwb - Welded bar
Qwe - Wetland

pre-Quaternary
br - Bedrock

Geomorphic Map Unit Descriptions

Qaf - Artificial fill (Quaternary)

Refers to manmade structures of imported sediments or existing glacial sediments that have been heavily anthropogenically-modified through development of infrastructure. George's, Moon and Lovell's Island all have large regions of modified till or fill.

Qdr - Drumlins (Quaternary)

Refers to upside-down spoon-shaped hillocks of glacial till deposited beneath an ice-sheet. Boston Harbor is the only drowned drumlin field in the United States, and many of the drumlins have been heavily eroded by coastal processes. Probably Illinoisan in age (800,000 to 300,000 years old), the drumlin core is composed of the of two glacial deposits in Boston Harbor, and are primary source of sediment for many of the surface geomorphological features. For a full description of the drumlin field see: Newman, W.A., Berg, R.C., Rosen, P.S., and Glass, H.D., 1990. Pleistocene stratigraphy of the Boston Harbor Drumlins, Massachusetts, *Quaternary Research*, v. 34, p. 148-159.

Qds - Dune system (Quaternary)

Refers to sandy shoreline deposits, aeolian in nature and stabilized by dune vegetation. There are few of these systems in Boston Harbor and those that do exist are small because of the lack of sand and sandy beaches. The largest dune system exists on Lovell's Island.

Qgfd - Glacio-fluvial deposits (Quaternary)

Refers to glacial outwash and delta deposits consisting primarily of bedded sand and gravel. These deposits are found primarily on Thompson Island.

Qgr - Gravel ridge (Quaternary)

Refers to wave built ridges consisting primarily of gravel with subsidiary coarse sand and shell. In many places gravel ridges have formed between two drumlins or have welded to the side of a drumlin. Overwash terraces are commonly associated with these features and in some cases a marsh may form in the sheltered region behind the ridge. The coarse sediment in the ridge allows some tidal exchange with the ocean, without the necessity of an inlet (for example, on Calf Island).

Qi - Inlet (Quaternary)

refers to tidal inlets; channels which allow water to flow between marshes or lagoons (that sheltered behind barriers) and the open water of the Harbor. These features have distinct geomorphology and

sedimentary signatures (see FitzGerald D.M., Geomorphic Variability and Morphologic and Sedimentologic Controls on Tidal Inlets *Journal of Coastal Research*:S123. pp. 47-71).

Qib - Intertidal bar (Quaternary)

Refers to linear deposits of sediments with elevations close to mean sea level that are covered at high water and exposed at low water. In Boston Harbor there are two notable types of intertidal bars: sediment convergence sites, such at the bars associated with the Salients (sites of sedimentation accumulation) on Thompson, Bumpkin, and Grape Islands; or deposition sites which have a core glacial till or lag (i.e. where finer sediment has been winnowed away by ocean waves and currents to leave just gravel and boulder size sediment), such as the bars reaching offshore from Great Brewster Island.

Qk - Kettle (Quaternary)

Refers to a depression in glacial-fluvial sediment left by the melting of an isolated ice block. These features are normally formed during glacial retreat. Kettles found in Boston Harbor are exclusively found on Thompson Island, which is partially composed of glacial outwash sediments.

Qla - Lagoon (Quaternary)

Refers to a body of water that is sheltered from the open water behind a barrier, but experiences some exchange with those open waters. They are often associated with marshes. A lagoon may have a direct connection to open water through a tidal inlet, such as the lagoons on Thompson Island, or may experience minimal exchange during certain stages of the tide or during storms, due to overtopping of or percolation through a gravel barrier/ridge. Examples of this latter type include the lagoons found on Peddocks and Calf Islands.

Qmp - Marsh pond (Quaternary)

Refers to shallow, water-filled, vegetation-free depressions found in a marsh system.

Qmrt - Marine-reworked till (Quaternary)

Refers to deposits of sediment existing in gaps between drumlins (or bedrock islands) that have led to islands merging to form one unit (for example the northerly drumlin complex on Peddocks Island). The sediment comprising these deposits have been reworked from older glacial sediment, including proximal drumlins, by marine processes (waves, tides, storms) as well as wind transport and surface run-off.

Qot - Overwash terrace (Quaternary)

Refers to deposits in the lee of barriers or in the center of a Salient that are deposited by storm waves creating layers of shell, gravel or sand with a shallow dip landward.

Qsa - Salient (Quaternary)

Refers to a deposit of sediment, which protrudes orthogonally from a shoreline. Salients are often formed because of the convergence of two longshore sediments transport cells. Where the offshore is characterized by a shallow platform, salient formation may result in an associated offshore bar (e.g. south of Thompson Island), but if there is a deep channel offshore, the salient form is limited to an obtrusion from the shore (e.g. along the southwest shore of Long Island).

Qsp - Spit (Quaternary)

Refers to a linear deposit extending offshore from a curving shoreline. Spits are created as sediment is moved downdrift from the source by wave-driven longshore transport. The direction of progradation is determined by wave climate and usually the orientation of the spit is directly related to the dominant approach of wave energy. In Boston Harbor, many spits have formed on both sides of a drumlin in the sheltered space between two drumlins (or bedrock islands), eventually linking the two islands. Overwash and aeolian processes commonly infill the lower lying area between the spits creating a linear island. Spits are generally composed of sand or gravel. Examples of spit-connected islands include Long and Peddocks Islands.

Qt - Tombolo (Quaternary)

Refers to a sand or gravel spit, which has formed in the lee of a topographic high, which in Boston Harbor is often a bedrock outcrop or drumlin. Formation of a tombolo occurs when longshore transport along the main shoreline is interrupted, causing deposition of sediment, which results in bar formation that grows outward from the mainland to connect with island.

Qtc - Tidal channels (Quaternary)

Refers to channels within marshes or lagoon systems through which tidal waters can flow.

Qtcb - Till-covered bedrock (Quaternary)

Refers to glacial sediments deposited over a bedrock core. Within Boston Harbor, two different age glacial till have been identified. The older of the two tills is thought to have formed drumlins, whereas the younger drift (the upper till) was deposited in late Wisconsinan time (up to 15,000 ybp) mantling the older till. The late Wisconsinan sequence includes thin, discontinuous drift composed of gravel, sand, and till see: Newman, W.A., Berg, R. C., Rosen, P.S., and Glass, H.D., 1990, Pleistocene stratigraphy of the Boston Harbor Drumlins, Massachusetts, *Quaternary Research*, v. 34, p. 148-159.

Qtf - Tidal flat (Qauternary)

Refers to a large flat intertidal platforms, often consisting of fine sediment.

Qwb - Welded bar (Quaternary)

Refers to a spit, tombolo, or gravel ridge that has welded to headlands at both ends, such as two drumlins and/or bedrock islands. In many cases the islands of the harbor comprise several drumlins linked by welded bars.

Qwe - Wetlands (Quaternary)

Refers to vegetated areas that are constantly or almost constantly inundated with water (fresh or salt). These include saltmarshes (either embayed or fringing the beach), and transitional fresher marshes that are formed in Boston Harbor in low lying areas behind welded bars. The latter may have originated as a saltmarsh, becoming increasingly freshened by decreased exchange with the ocean (as the barrier widens and builds vertically). This process is usually accompanied by an encroachment of transitional vegetation such as *Phragmites*.

br - Bedrock (pre-Quaternary)

Refers to significant outcrops of bedrock, which are exposed at high tide or for the majority of a tidal cycle.

GRI Digital Bedrock Geologic Map of Boston Harbor Islands National Recreation Area

Bedrock Map Unit List

The bedrock geologic units present on the GRI Digital Bedrock Geologic Map of Boston Harbor Islands National Recreation Area are listed below. Units are listed with their assigned unit symbol and unit name (e.g., JZd - Diabase/Doleritic dike, undifferentiated). Units are generally listed from youngest to oldest. No description for water is provided. Information about each bedrock geologic unit is also presented in this dataset's Bedrock Geologic Unit Information (BHBRUNIT) table included with the GRI bedrock geologic-GIS data.

Mesozoic Era and older

JZd - Diabase/Doleritic dike, undifferentiated
J(?)Zib - Intrusive breccia
J(?)Zdo - Doleritic sills and dikes, undifferentiated

Paleozoic Era

SOqgr - Quincy Granite

Paleozoic Era and older

CZca - Cambridge Argillite
Zdm - Diamictite

Precambrian

Zcr - Roxbury Conglomerate
Zvt - Tuff
Zvm - Melaphyric Volcanics (after Crosby, 1893 and 1894)
Zvp - Porphyritic Volcanics (after Crosby, 1893 and 1894)
Zgr - Granitic plutonic rocks, undifferentiated

Bedrock Map Unit Descriptions

No unit descriptions were provided by the source map authors. Some units are referenced in the bedrock report.

Bedrock Cross Section

The geologic cross section present in the GRI digital bedrock-GIS data produced for Boston Harbor Islands National Recreation Area is presented below. The graphic is high-resolution and can be viewed in more detail by zooming in (if viewing the digital format of this document).

Simplified Cross Section along the Inter Island Tunnel

**To access the cross section double-click the link above.

Bedrock Geology Report

A Report on the Bedrock Geology of Boston Harbor to the National Park Service.

Peter J. Thompson (1), Joseph P. Kopera (2) and Daniel Solway (3)

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Part I. Overview of the Bedrock Geology of the Hull 7 ½' Quadrangle and Vicinity

Background

The bedrock geology of Boston Harbor has been studied for more than a century, but a full understanding of its geological history is only now emerging, thanks to information from tunnels beneath the harbor and to modern analytical techniques. William O. Crosby (1880, 1889, 1893, 1894) produced excellent, detailed maps of the rocks along the southern margin of the basin from Quincy to Nantasket. Crosby (1880, 1888) also described in words the geology of the islands in the harbor, and his observations and conclusions, for the most part, stand unchallenged. Crosby's unpublished field notebooks were consulted at the MIT Libraries Archives. Five islands (Green, Calf, Middle Brewster, Outer Brewster and Rainsford) were mapped by personnel of Hager & Richter at 1:2500 as part of a study before construction of the Inter-Island and Outfall Tunnels (Metcalf & Eddy, Appendix I, 1989).

Boston and its harbor lie in a down-dropped basin bordered by faults. The Boston Basin is part of the Avalon terrane, a continental fragment that became attached to the rest of North America in Paleozoic time. The rocks in the basin were deposited much earlier, in the late Precambrian, when Avalon was located at mid latitudes south of the equator, off the western coast of Gondwana (Thompson et al., 2007).

Other maps that include the Hull Quadrangle (Zen, 1983; Billings, unpub.; Kaye, unpub.) have imposed a stratigraphy developed to the west in Boston (Emerson, 1917; LaForge, 1932; Billings, 1976) onto the islands and the harbor's perimeter. According to this stratigraphy, the Boston Bay Group is comprised of two formations: the Roxbury Conglomerate, containing three members, and the Cambridge Argillite, in which Lenk et al. (1982) found Precambrian microfossils. Shaler (1869) named the fine-grained, presumably youngest, unit in the Boston Bay Group, the Cambridge Slates. Billings (1929), noting the massive character, referred to the same rocks as the Cambridge Argillite. Billings (1976) presented evidence for a facies relationship between these two formations, whereby the Cambridge both interfingers with and overlies the Roxbury, depending on where you are in the basin. Billings also pointed out that all three members of the Roxbury Formation contain conglomerate, melaphyric volcanics, sandstone and argillite in varying proportions: the lowest, the Brookline Member, is dominantly conglomerate and volcanics, the middle Dorchester Member has far more sandstone and argillite, and the Squantum Member contains clast-supported conglomerate and matrix-supported diamictite. Most geologists (for example Dott, 1961; Socci and Smith, 1990; Bailey and Bland, 2001) now regard the diamictite as debrite (formed by subaqueous debris flows) rather than as tillite (deposited as glacial till, for example, Sayles, 1914; Rehmer and Hepburn, 1974). Bailey et al. (1976) summarized the history of the debrite/tillite controversy and argued that any hypothesis must be compatible with evidence from other units in the Boston Bay Group.

Bailey and Bland (2001) presented a cogent depositional model for the Boston Bay Group whereby the sedimentary rocks represent a sequence of continental to marine facies, which gradually filled a basin on rifted Neoproterozoic basement of Dedham Granite (608 Ma, Thompson et al., 2010) and melaphyric Mattapan Volcanics (~596 Ma, Thompson et al., 2007). According to this model, coarse clastic sediments are most common at the base, but also appear higher in the stratigraphy, deposited by debris flows that swept out into the deepening basin from time to time. Socci and Smith (1990) came up with a similar model, but suggested that glacial processes strongly influenced the sedimentation. They also argued that the traditional mapping of all diamictite horizons from place to place as the Squantum Member, which Billings (1976) assumed was unique in the stratigraphic section, had become suspect. Thompson (1983) showed that thickness changes and clast assemblages in the lower conglomerates could be related to sub-basins defined by ENE-trending faults. Some of the rift faults may have been reactivated as reverse faults during later deformation. A model of interfingering facies best explains the sandy argillite, numerous thin sandstones and rare diamictites and conglomerates reported within the argillite in the islands and along the Inter-Island Tunnel.

Scope of Present Study

The present authors mapped at 1:1000 all the larger islands in Boston Harbor where bedrock is exposed: the Brewsters, Graves, Green, Calf, Rainsford, Hangman, Raccoon, Grape, Slate, Langlee, Ragged, Sarah and Button. In addition, we studied tunnel and borehole records (Metcalf & Eddy, 1989) from the Inter-Island Tunnel, which carries waste water from Nut Island north to Deer Island treatment plant, and borehole records from the Outfall Tunnel, which carries treated effluent ENE to a point beyond Graves Light. Unpublished notes from the Braintree-Weymouth Tunnel were provided by Margaret Thompson (pers. comm., 2011). Richard Bailey provided measured stratigraphic sections and unpublished maps for Slate Island, Hewitts Cove and Worlds End. Martin Ross sampled igneous rocks on Calf and Middle Brewster and interpreted the resulting geochemical analyses.

Sedimentary and Volcanic Rocks

The bulk of the sedimentary rocks in the Boston Harbor islands and Inter-Island Tunnel are fine-grained, laminated, gray to pale green to purplish-gray or black Cambridge Argillite. The thin bedding and other sedimentary features in these rocks are typical of turbidites, deposited when fine sediment slowly settles out onto the sea floor from a turbidity current. Crosby (1888) referred to these rocks as slate, but true slaty cleavage is well developed in only a few places, such as the north arm of Rainsford Island and on Slate Island, where slate was quarried starting in colonial times (Snow, 1971). Ring fossils that are identical to structures found in England and Wales, where the age is well constrained as Late Neoproterozoic by dated volcanic ash (Bailey and Bland, 2001), have been found in numerous localities on the islands and on shore.

Rocks in the central and north parts of the harbor are dominated by tan-weathering, greenish gray argillite. Numerous sedimentary structures such as cross-beds, dewatering structures and slump folds provide original topping information; no beds are overturned except in isoclinal, intrastratal slump folds, best exposed on Rainsford Island. Approaching Nut Island in the Inter-Island Tunnel, beds steepen and become overturned. In the southern part of the Inter-Island Tunnel, at Squantum and at Hull, and along the southern harbor, argillite tends toward purplish or reddish brown. Crosby (1880, p.203) wrote, "…no sharp distinction is possible between the brownish and grayish slates. The most that can be said is, that the slate immediately overlying…conglomerate is very likely to be of brownish or purplish tints, and that these colors are rare in slates not occupying this stratigraphic position." In the Inter-Island Tunnel the break between gray and purplish colors occurs south of a major fault zone south of Rainsford Island. Sandy argillites and very fine grained sandstones are common throughout the tunnel. Some of the sandier layers may be tuffaceous (Metcalf & Eddy, 1989). Unfortunately, no stratigraphic pattern or marker horizon seems to stand out, which would help define the structure within the argillites more closely.

Diamictite is exposed in the Hull 7 ½' quadrangle mainly at Moon Island, which is on strike with identical rocks along the south shore of Squantum, all dipping south. Another layer of south-dipping diamictite holds up the ridge of Chapel Rocks on the north shore of Squantum (fig.1), which is generally taken to be the type locality of the "Squantum Tillite" (Sayles, 1914). Billings (1976) interpreted the two diamictite layers as one and the same, repeated by a fault. Kaye (1980) incorrectly showed the southern layer dipping north, with a syncline between the two. We agree with an alternative hypothesis (Socci and Smith, 1990), that the two diamictites represent two separate debris flows. The argillite above and below the Chapel Rocks layer appears virtually identical: purplish-gray, with sandy interbeds, yet according to Billings that below is the Dorchester Member and that above is the Cambridge Argillite. Clarke (1885) reported a conglomerate layer dipping south in the sewage tunnel between Squantum and Dorchester. He did not note whether it is clast-supported or matrix-supported, but perhaps it is a yet a third diamictite layer. Billings (1976) assumed it to be the Squantum Member, repeated by another fault. Crosby (unpub. notebook no.2, 1886) inspected the material from the tunnel, which included mostly argillite, with "a little slaty conglomerate". Geologists who logged boreholes north of Long Island (Metcalf & Eddy, 1989) reported "conglomeratic argillite", which we interpret as diamictite, within the argillite. More than one diamictite layer would be more consistent with Bailey and Bland's (2001) depositional model for the Boston Bay Group than would a unique stratigraphic position.

Volcanic rocks (andesitic basalt), conglomerate and argillite are found along the south shore of Boston Harbor. These rocks are apparently in fault contact with the argillite lying under the harbor and exposed at Hull, Grape Island and Slate Island. Billings (1976) extended the Blue Hills thrust fault from where it was formerly well exposed in Milton, east along the harbor to the coast at Nantasket, stating that the best evidence is in Hingham, where conglomerate and volcanics are truncated against the argillite (see Structure section below). 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 World's End.

Igneous Intrusions

Dolerite sills and dikes intrude the Cambridge Argillite, and in fact are responsible for the presence of the outer islands, which otherwise would have been eroded away below sea level. Crosby (1888) noted how the relationships between the igneous rocks and the argillites provide textbook examples of intrusive relationships, including chilled margins and cross-cutting relationships. However, a closer examination shows that in many instances, the argillite both above and below some sills appears to have melted and recrystallized, rather than being altered by contact metamorphism.

The boundary between the doleritic and felsic rocks is scalloped, as though between immiscible liquids, and veins of felsite intrude the doleritic rock, locally enclosing pillows of fine-grained dolerite along the borders of the sills (fig.2). Crosby (unpub. notebook no.1, 1901) described such pillow-like shapes as a "marble paper pattern". He wrote in notebook no.4 (1901?) "[there is] much evidence that the slate was not thoroughly lithified when the [dolerite] was intruded." We agree, and by extension, conclude that the sills are also Neoproterozoic. These relationships were carefully described on Calf Island by Janet Sarson (1998), who also studied the petrography and geochemistry of the sills. She found that some of the dolerite is picritic. All of the sills are altered: olivine is replaced by phyllosilicates, plagioclase laths are cloudy in thin section, and pyroxene is locally rimmed by amphibole. Why the argillite melted rather than undergoing contact metamorphism may have had something to do with the amount of water still present in the sediments, which would have lowered their melting temperature.

New geochemical analyses of samples from several Boston Harbor dolerite sills plot in the subalkaline tholeiitic basalt field of geochemical diagrams (Ross, pers. comm., 2011). This is in contrast to dolerite sills and dikes at Nahant, which are more alkaline (Bailey and Ross, 1993). A 20 meter-thick, east-west dike on Calf Island and a thinner one on Middle Brewster have chemical compositions distinctly different from the sills, suggesting that they probably did not serve as feeder dikes for the sills. These dikes are more like some of the Nahant dikes and sills, as well as many of the

Paleozoic dikes of the Avalon terrane in Massachusetts (Ross, 1990). Some of the NE-trending dikes could be Mesozoic, which is the commonest orientation for Mesozoic dikes in coastal New England (McHone, 1978). Basalts form in a wide variety of tectonic settings, and geochemical discrimination diagrams have been used to compare ancient basalts to those in known, modern settings. Geochemistry suggests that the Boston Harbor dolerite sills were most likely intruded in a plate margin, island arc or back arc setting. Again, this is in contrast to the Nahant sills and the cross-cutting east-west dike on Calf, whose geochemical pattern is more typical of a continental arc or within-plate setting (Ross, pers. comm., 2011). A back arc setting for sills in the Cambridge argillite is consistent with the traditional view of a within-plate, subduction-related environment (Cardoza et al., 1990), in a wrench or transtensional basin (Nance, 1990).

Felsic sills and dikes are quite abundant along the Inter-Island Tunnel, especially near Rainsford Island. A sill about 30 cm thick crops out on Rainsford, with quite unusual chemistry: low in silica but high in alkalis, it plots as a basanite (Ross, pers. comm., 2011). Tan-weathering, fine-grained dacite sills and thin dolerite sills intrude the argillites on Grape and Slate Islands.

Structural Geology

Crosby (1888) was the first to recognize the Brewster syncline, an open fold plunging about fifteen degrees northeast between Calf Island and the Brewster Islands. The fold deforms both the Cambridge Argillite and the intruding dolerite sills, which proves that the deformation happened after the sills formed. Crosby (1888) speculated that the same synclinal fold extends southwest through Rainsford Island and North Quincy ("Wollaston syncline" of Billings, 1976). This is exactly what we see in the Inter-Island Tunnel: a broad region of gently folded rocks, but overall synclinal in form, from about Long Island south to an important fault zone between Rainsford and Peddocks Island.

North of Long Island argillite and dolerite sills observed in the Inter-Island Tunnel are arched by a broad anticline, which is the eastern extension of the Central anticline on the mainland (Billings, 1976). A stereonet plot of bedding attitudes across the anticline shows that the axis trends N47°E and plunges 20°NE. Cleavage dips steeply to moderately northwest, roughly parallel to the axial plane. Boreholes along the Outfall Tunnel alignment ENE of Deer Island cross the broad nose of the Central anticline and then follow the north limb of the Brewster syncline.

The Main Drainage Tunnel, which passes under Castle Island on its way to Deer Island, lies parallel to the north limb of the Central anticline (Rahm, 1962). The corresponding syncline to the north, the Charles River syncline, appears in the North Metropolitan Relief Tunnel at the very NW corner of the Hull 7 ½' quadrangle (Billings, 1975). Morell et al. (2004) found that a stereonet plot of bedding defines a fold axis at N54°E plunging 12°NE, very similar to that for the Central anticline. However, the axial plane of the syncline and associated cleavage dip steeply southeast. Morell et al. (2004) noted a second, north-dipping cleavage in a few borehole samples, which they suggested may be related to younger, south-verging folds. Cleavage in the Inter-Island Tunnel dips almost exclusively northwest. The exact age of the folding is unknown. Skehan and Murray (1980) believed it to be due to the late Paleozoic Alleghanian orogeny. In their view, the earlier Taconian and Acadian orogenies did not affect any of the Avalon terrane southeast of the Bloody Bluff fault.

Although evidence for faulting was observed along the entire length of the Inter-Island Tunnel, many of the slickensided joints and even thin breccia zones do not show much displacement (Metcalf & Eddy, 1989). Slickensides on bedding planes indicate flexural-slip folding. All faults with reported zones of gouge and offset beds are shown on the map and in the tunnel cross-section. Even some of these, for example faults near Long Island, do not disrupt the overall dip of the bedding. If the Mt. Hope fault (Billings, 1976; Kaye, 1980, Thompson 1983) extends northeast into the harbor, it is unclear which if any of the faults in the tunnel correspond. We see no evidence for major faults on either side of a Squantum-Moon-Long Island block, which Billings (1976) invoked largely because of his assumption of a unique diamictite horizon.

Several major faults do cut the stratigraphy and folds south of Rainsford Island, where the Brewster syncline is abruptly truncated. Some of these were predicted by "low-velocity zones" detected by seismic reflection surveys prior to the tunnel construction (Metcalf & Eddy, Appendix K, 1989). A major zone of altered, rotten rock some 400 feet thick was encountered in the tunnel and provided significant engineering challenges. The dominant faults strike NE and they may continue along the bathymetric lineament that extends NE between the Brewsters and Hull. Toward the SW, the fault zone may correspond to an unnamed fault south of the Wollaston syncline (Kaye, 1980).

In Hingham an E-W fault, perhaps an extension of the Blue Hills fault (Billings, 1976), truncates a complicated, faulted pattern of Boston Bay Group rocks, adapted on our map from Crosby (1894). A similar fault was observed during construction of the Braintree-Weymouth sewage tunnel south of the shaft on Nut Island, west of Raccoon Island (Deere et al., 2004). The fault dips 73°N (Thompson, pers. comm., 2011), with Cambridge Argillite on the north against a south-facing sequence of volcanics, conglomerate and argillite. South of Germantown, in the Weymouth Quadrangle, the same tunnel intercepted a "healed thrust fault" between Cambridge Argillite and the Cambrian Weymouth Formation (Deere et al., 2004). These faults may be a manifestation of the same compression that formed the Central anticline and Brewster syncline. At the south margin of the basin, the more massive granite, conglomerate and volcanics may have folded less easily, with the result that the argillite was thrust south on top of them.

Part II. Bedrock Geology of the Boston Harbor Recreational Park Area

Introduction

The Boston Harbor Recreational Park Area encompasses some 34 islands, the peninsula of Worlds End in Hingham, and numerous rocks and islets barely above sea level. Of the 34 islands, 13 have no exposed bedrock: Snake, Deer, Thompson, Long, Spectacle, Georges, Gallups, Great Brewster, Lovells, Peddocks, Sheep, Bumkin, and Nut. Nixes Mate was quarried for slate in the eighteenth century to the point where no bedrock remains exposed above sea level. Extensive breakwaters, for example on Lovells Island, and the fort at Georges Island were constructed largely of Quincy Granite (fig.3).

The present authors visited and mapped 16 islands. The remaining four are small with difficult access, and we have relied on William O. Crosby's reports on them from the 1880's: Roaring Bulls, Little Calf, Shag Rocks and Quarantine Islands. Several of the larger, taller islands are drumlins, elongated hills of glacial till, which were streamlined by passage of the glaciers across them. Gallops Island and Bumkin Island, for example, consist of a single drumlin elongated in a southeast direction. Others like Peddocks and Long Island have multiple drumlins connected by tombolos made of sediment, which was eroded from the drumlins and redistributed by ocean currents. On still others, such as Great Brewster and Sheep Island, only a vestige of the original drumlin remains. Even where the ocean has cut into the drumlins, no bedrock cores have appeared; the steep cliffs of till at Great Brewster, Prince Head and Allerton Hill, for example, all descend directly to a flat shoreline (fig.4). Moon Island is an exception, in that erosion of its drumlin has revealed an outcrop beneath the till.

Little Brewster Island

Little Brewster Island, the home of Boston Light since 1780 (and earlier lighthouses since 1716), is composed of Cambridge Argillite intruded by several sills of dolerite. The argillite is a very fine-grained, thinly bedded, pale gray to tan-weathering rock that breaks into angular blocks. Slump folds on the peninsula east of the lighthouse suggest that the original muddy sediments were deposited offshore, on the continental slope, where they slumped and produced turbidity currents. Groove casts (fig.5) on bedding planes may indicate the direction such currents moved. Evidence from elsewhere in the Boston

Basin indicates a Neoproterozoic age for the Cambridge Argillite. Glacial striae south of the landing dock point S60°E and indicate the direction glacial ice passed over the island in very recent geological time.

The dolerite sills are dark brown-weathering, massive mafic rocks, which are more resistant to erosion than the argillite. On close inspection one can see small whitish feldspar crystals set in a mass of darker pyroxenes and other minerals. Most of the sills on Little Brewster are relatively thin, 50 to 100 cm thick, although the cliff below the lighthouse exposes two thicker sills (fig.6).

Crosby (1888, p.456), in his description of the "Geology of the Outer Islands of Boston Harbor" referred to the argillite as slate and the dolerite as diabase. He wrote, "Beds of slate are interstratified with and enclosed in beds of diabase, with many alternations of the two rocks. The relations of the slate and diabase are as plain as they well could be, and some of the enclosed fragments of slate are very beautiful". The best exposure of the "slate fragments" is north of the light keeper's house. Close inspection reveals that the felsic rock directly beneath the sill is a crystallized melt derived from the argillite below, when the hot basaltic magma intruded roughly parallel to bedding in the argillite. Flat fragments of argillite are scattered at haphazard angles within a 10 cm zone of felsite, incorporated from the underlying bedded argillite. The margin of the overlying mafic rock is fine-grained as though chilled against the felsite, and it has an irregularly scalloped shape, suggesting that the two liquids were immiscible and cooled against each other (fig.7). At the west end of the lighthouse cliff, pillow-like forms of dark dolerite are enclosed by a light-colored, felsic material, which connects to the argillite.

All the rock layers on Little Brewster strike NE and dip 30° to 50°NW. They were tilted from their original horizontal position and now lie on the southern limb of a large syncline opening eastward. The axial trace of the fold lies between the Brewster Islands and Calf Island. A few minor folds on Little Brewster mimic the trend and plunge of the Brewster syncline, most notably one plunging 15° toward N50°E, which deforms the sill immediately north of the light keeper's house (fig.8).

Crosby (1888) noted that the rocks on Little Brewster are similar to those seen on Middle and Outer Brewster nearby to the north, which also dip NW. He suggested that the Middle and Outer Brewster section might be repeated on Little Brewster by virtue of a normal fault, downthrown on the south side. We have no evidence to refute this hypothesis, but noting that several dolerite sills also appear in the Inter-Island Tunnel, we expect that many sills intruded the Cambridge Argillite at different stratigraphic levels. The sills on the other Brewsters and Calf are much thicker, and we interpret them to be at a higher and younger level than those at Little Brewster (see cross-section A-A'). We will discuss evidence on other islands for multiple episodes of sill intrusion, but even on Little Brewster one can see thin basaltic sills cutting across thicker sills. Some of the sills are also connected to each other by layers that cut across the argillite, for example the dolerite under the lighthouse keeper's house is an undulating but nearly flat layer, which connects to the sills north of the house.

The rocks on Little Brewster do not show much evidence of faulting, although many joints show some offset, especially in the flat area northeast of the lighthouse, where numerous joints crisscross several thin dolerite sills. Slickenlines are preserved on some joint surfaces, for example at the overlook southwest from the lighthouse. Notches in both the north and south cliffs define a zone of apparently highly fractured bedrock, reinforced by rip-rap and wire mesh. The zone strikes north-south about ten meters west of the lighthouse. Layers on either side of the notch show no displacement, so it is unlikely that it represents a fault. It could be a vertical dike, but no rock is exposed. South of the light keeper's house at low tide, one sill is offset several centimeters, down on the west, by a small NW-striking vertical fault. A small fault along the north shore has a similar strike but opposite sense of offset.

Shag Rocks are a continuation of the south part of Little Brewster; the north dip steepens to about 65° at the east end (Crosby, unpub. notebook no.4, 1901?). Crosby reported a "fine natural arch", whose supporting pillar is "quite narrow, and apparently must soon give way". Has anyone seen it

recently?

Middle Brewster Island

Two thick dolerite sills dominate the geology of Middle Brewster Island. The rock layers strike ENE, parallel to the length of the island, and dip about 30 to 50°NW. The argillite underlying the lower sill is exposed along much of the southern shore, where waves pounding cobbles against the cliff have produced some very fresh surfaces. It is a pale greenish gray to white, thinly bedded, very fine-grained rock. Beautiful soft-sediment structures, rip-up clasts, and dewatering structures are preserved, especially toward the west end of the island (fig.9). About midway along the southern shore a thinner layer of dolerite intrudes the argillite, and the whole section is deformed into a sharp drag fold associated with a thrust fault with minor displacement above it. At the west end of this cliff, near an old foundation on the bluff and the only landing place on the island, a NW-striking, vertical basalt dike cuts the argillite. The chemistry of this dike is similar to a thick E-W dike on Calf Island (see Igneous Intrusions section). A second, parallel dike can be found along the cobble beach west of another foundation and a grove of Chinese elms. A third basalt dike in the small cove at the west end of the island has a strike parallel to the sills but dips 60° south.

The upper dolerite sill has chilled margins where it overlies the argillite at the west end of Middle Brewster, and also where it overlies the lower sill toward the east end, showing that the upper sill is the younger one. At the east end the lower sill has a pillowed structure along the contact, as though argillite formerly between them was cut out by the upper sill. Thus the upper sill intruded obliquely across the first. Thin basalt sills, at most two meters thick, lie parallel to the upper sill, both in the argillite at the west end and in the lower sill at the east end. Of these thinner sills, Crosby (1888, p.456) wrote: “sometimes the diabase, which is finer-grained here than in the larger masses, jogs across the slate, or two intrusive beds gradually approach and unite... we may safely pronounce these the finest exposures of intrusive beds in the Boston Basin.” The two main sills are coarse-grained, dark dolerite with alternating layers of more felsic composition, some of which are coarse enough to be described as pegmatitic (fig.9A). The uppermost part of the upper sill where it dips into the ocean is massive, reddish-weathering, and overlain at the west end by a pillowed zone similar to those on Little Brewster and Calf. We suppose that argillite formerly covered this pillowed zone, and that the bay between Middle Brewster and Calf is mainly underlain by argillite. The resistant sills are therefore responsible for the presence of the island which, if it were only made of argillite, would have been eroded down below sea level.

The interior of Middle Brewster is more open than some of its neighboring islands, with old pastures growing up to sumacs amid old stone walls. Several zones of strongly foliated, greenish-weathering, altered dolerite cross the island, most of them roughly parallel with the thick sills. However, one of the foliated bands strikes NE, and the foliation within the band strikes obliquely ENE, parallel to foliation elsewhere. A large patch of foliated rock is well exposed between an old chimney and a stone arch. Glacially scoured grooves and striations that decorate the surface of the outcrop indicate ice motion toward S60E (fig.10). Curved joints have encouraged erosion of the upper sill into curious dome-shaped knobs at two locations: one south of the little cove at the west end, and one near a deep square notch along the north shore (fig.11). Crosby (unpub. notebook no.4, 1901?) described a huge “rotating boulder” in a basin along the north shore, covered at high tide.

Outer Brewster Island

The lower sill on Middle Brewster is directly on strike with the west end of Outer Brewster, across “the Flying Place” (fig.12), and indeed very similar, coarse dolerite with four or five parallel basalt sills is exposed on both sides of the strait (fig.13). The top of the sill continues along the north shore, dipping 50 to 60°NW (fig.14). The dip lessens and the strike gradually shifts more easterly and then ESE, dipping more gently at 20 to 30° at the east end of Outer Brewster. Argillite is exposed along the south shore, which is mostly inaccessible except at very low tide. Near the old desalinization plant the contact is well exposed, and it appears that the dolerite is chilled against the argillite without the disturbed, melted zone seen on Little Brewster and Calf Islands. The argillite pinches out toward the

east as the contact steps down across the bedding. Farther east the argillite reappears below the dolerite in the center of a broad, gentle anticline that apparently trends north (fig.15).

Small outcrops in the interior of Outer Brewster Island show that the thick dolerite sill is gently deformed by folds at a high angle to the one exposed along the south shore. One anticline reaches a deep ravine that crosses the island toward the east end, and in the center of the fold some argillite peers out from underneath the sill. The argillite does not appear on the east wall of the ravine, suggesting that the ravine marks a fault, with the east side moving down. Snow (1971) reported that Arthur Austin quarried stone from the ravine in 1843 for macadam in Boston and started to cut a canal for anchorage. No evidence for quarrying was noted.

Northwest trending joints along the north shore and around the east end cut the coastline into distinct blocks. Some of these joints have slickenlines, but little offset. Immediately east of the landing cove two sharp ravines are clearly faults, one with vuggy quartz and slickenlines down the dip, and the other with a meter-wide breccia zone striking toward Green Island (fig.16). Slickenlines suggest the west side moved down and to the north. On the south shore a foliated zone with the same northwest strike lines up with the faults and the landing cove. A trail leads from the cove to the northern of two WW II gun batteries, and near there along the top of the north cliff one can find the remains of an old coal pile, clearly visible on satellite images. Farther to the west, beyond the westernmost barracks, a two-meter basalt dike strikes S64°E and dips 62° SW.

Calf Island

The thick dolerite sills on Middle Brewster reappear on Calf Island on the northern limb of the Brewster syncline. Crosby (1888, p.456) wrote, “It is very obvious that in passing from Calf Island to the Brewsters we have crossed an important synclinal axis, all the rocks to the northwest of this channel – eruptive as well as sedimentary—dipping southeast, and all those to the southeast of it dipping northwest.” At least three sills of variable thickness are exposed across Calf Island. The lowest one forms the northwest shore, where it is overlain by thin argillite and a second sill. The sills have pillowy shapes in a felsic matrix along the argillite contacts. All these rocks are cut by a 20 meter, vertical dolerite dike striking east (fig.17). The dike is offset at least ten meters south by a north-striking fault in the center of the island, and reappears on the east side where, being more strongly jointed than the dolerite sills, erosion has created a jagged headland (fig.18). Epidote-rich lenses in the dike near the fault are elongated parallel to NE-striking joints in an en echelon pattern that suggests right-lateral shear.

A thickness of more than ten meters of argillite is exposed south of the landing cove on the west shore of Calf Island, dipping 22°E below a prominent cliff of dolerite (fig.19). The argillite strikes inland toward a large salt marsh, and is apparently offset by faults across the low-lying middle of the island, for the argillite is not exposed east of the marsh. Walking south along the top of the dolerite cliff, one sees dark mafic-rich bands a few centimeters thick, which locally merge (fig.20). Perhaps they were formed by flow of magma within the sill, or by successive multiple injections of magma. Toward the next cove south the sill becomes altered to a greenish color, underlying a reddish sill, which has a chilled margin against the greenish rock (fig.21). Samples from both sills near the contact are picritic dolerite, rich in altered olivine.

The argillite reappears on the next promontory south, a spot much favored by nesting sea birds, where it is arched beneath the dolerite sills in an open anticline. Cleavage in the argillite strikes NE, parallel to the fold’s axial plane, and dips 75°NW. From here southeast below the ruins of actress Julia Arthur’s 1891 ”cottage”, a tall cliff exposes a series of dolerite sills that were studied by Wellesley College student Janet Sarson (1998). Sarson concluded that the thin layers of argillite preserved between the sills, much like the situation north of the landing cove, seem to have partially melted in contact with the hot intruding magma. The felsic melt in turn was injected into cracks in the cooling dolerite, both above and below the argillite (fig.22). The felsite and argillite are geochemically identical (Sarson, 1998). The disturbed felsic zone is about ten centimeters thick and contains flat clasts of

unmelted argillite identical to those observed on Little Brewster Island. At the south end of the cliff, all these layers are cut by a steep fault, beyond which much of the dolerite is greenish-weathering and foliated (fig.23). The foliation wraps around some curious, roundish masses of unfoliated dolerite a few meters across, best exposed at the southern promontory. Crosby also noted these masses and on his third visit to Calf (unpub. notebook no.4, 1901) wrote that they were “still a mystery”! The foliation is steep and strikes NE, reappearing along the east shore 50 meters north of yet another exposure of argillite and dolerite pillows with felsic matrix. It would seem that the foliated zone must be a shear zone, because the argillite strikes northwest toward the interior of the island, at a high angle to the foliated rock. Farther north along the east shore, well-layered dolerite is deformed by open folds that plunge gently east (fig.24). Folds are apparent on a satellite image as two dish-shaped synclines opening southeast toward the Brewster Islands.

Little Calf Island

We did not land on Little Calf Island, but it seems to be a continuation of the dolerite from the north end of Calf Island. Layering dips SE but then curves around to dip NE in an open anticline. The name “Calf” apparently is a corruption from “Calef”, after one Robert Calef who may have owned the islands in early settlement days (Snow, 1971).

Green Island

Green Island is very rocky, with one vegetated slope tilted toward Calf Island, from which it is separated by a deep channel, including the 100-foot deep hole called “The Hypocrite”. This channel may follow a fault striking about N82E. Two vertical faults create sharp notches at the sandy cove on the west side of Green Island near an old sunken barge, and one thin layer of argillite too thin to map is exposed just north of the cove. The rest of the main island is entirely made of coarse dolerite, with massive layers that dip from 17°to 25°ESE. Glacial striae point S71°E.

At low tide a curious breccia zone is exposed among the smaller islands southwest of Green Island. It is up to 30 meters wide. A felsic matrix encloses clasts of argillite, dolerite and basalt, which range in size from a centimeter to a meter across (fig.25). Some clasts are angular and could be fit back together like pieces in a jigsaw puzzle (fig.26), while others are rounded as though abraded by movement in the felsite, or partly resorbed. The matrix looks much like the felsic material associated with argillite interlayers on Calf and the Brewsters and has similar geochemistry (Ross, pers. comm., 2011). Could the breccia have originated in a similar fashion, and moved upwards from argillite underlying the dolerite of Green Island? The texture resembles what some geologists have called peperite, believed to form when hot mafic magma intrudes wet, partly consolidated sediments.

The Graves

Graves Light sits on a group of small rocky islands NE of Green Island, beyond a string of small islands called the Roaring Bulls. Crosby (1888) considered all these islands as an extension of the dolerite sill from Green. He reported an eight meter wide east-west dike near the south end of the Graves and several others farther north parallel to it. We photographed a thinner dike but did not land on the island (fig.27).

Rainsford Island

Two small, bedrock headlands bracket an arcuate beach on the south end of Rainsford. Gray to black argillite displays some of the most interesting folds in all the islands. Recumbent, isoclinal folds, in turn deformed by upright, open folds, are well exposed on the west promontory (fig.28) and at the east end of the beach. A strong cleavage (fig.29) lies parallel to the open folds’ axial planes. Primary sedimentary structures indicate that the sequence of argillite on the whole is upright, suggesting that the isoclinal folds are the result of soft-sediment slumping before lithification was complete. Such structures are common in turbidites and are exposed elsewhere in the Cambridge Argillite.

A tan-weathering basanite sill, 30 centimeters wide, dips 32°NW about 20 meters east of the

beach (fig.30). Several light-colored sills and dikes were also reported in the nearby Inter-Island Tunnel, which passes just to the west of Rainsford Island (GZA Environmental, 1995). Argillite continues around the promontory south and east of an old foundation. People arriving at Boston by ship, who were suspected of carrying contagious diseases, were held in quarantine at a hospital on Rainsford Island. Only the foundation blocks of Quincy Granite and names carved in the bedrock remain as testament to the building that served as a hospital from 1737 to 1849. Concretions from a few centimeters across to the size of footballs can be seen along the east shore (fig.31); these were also observed by geologists in the tunnel, who described them as argillite "dropstones". The inside of one concretion contains a radiating mass of calcite and pyrite veinlets, like those in a septarian nodule.

Quarantine Rocks

Four small islands in a north-south line south of Rainsford Island are known as Quarantine Rocks. The name cannot be literal, for the rocks hardly seem large enough to have been used for quarantine (fig.32), although a lobsterman did live there in a three-story house on stilts for some time (Snow, 1971). We did not visit the rocks, but Crosby (1880, p.215) noted that the beds of grayish black slate there are "most wonderfully contorted and folded; presenting anticlines and synclines of every variety, --large and small, open and closely folded, normal, inverted, and faulted." His description applies equally well to the folds on Rainsford. The cleavage dips 70°NW and a ten-foot thick dolerite layer dips at a low angle south through the northernmost of the Quarantine Rocks (Crosby, unpub. notebook no.3, 1901).

Sunken Ledge

Crosby (1880, p.215) reported that Sunken Ledge, which is not well exposed even at low tide, consists mostly of loose rocks, but one large mass appeared to be in place. "It is a brownish slate holding an occasional pebble, and evidently marking a passage between slate and conglomerate." This sounds like the matrix-supported, diamictic conglomerate of Squantum and Moon Island. Loose blocks of diamictite are also found on several of the islands: The Graves, Outer Brewster, Middle Brewster, Hangman and Slate. If they are glacial erratics, that would imply an exposure of diamictite somewhere northwest of each occurrence. That works for Sunken Ledge and Hangman, but there are no such exposures at the present erosion level NW of the other islands. Or were blocks of this rock used as ballast and dumped by passing ships, or brought to the islands for some other purpose? Crosby (1888) noted that someone had purportedly found a Paradoxides trilobite fossil in a block on Georges Island, raising similar questions. These Cambrian fossils are known in the Boston area only in the Braintree Argillite, south of the harbor.

Hangman Island

The geology on Hangman Island is remarkably interesting for such a small island. It illustrates many of the features seen on larger islands such as Calf. The western half is pillowed dolerite with minor argillite, which is offset about a meter to the north along a NW-striking fault. The contact between dolerite and argillite is scalloped much like that seen on Little Brewster. East of the fault, argillite crops out along the south shore, dipping gently north toward dolerite along the north shore. The contact is obscured by vegetation, but on the northeast corner of the island the dolerite contains numerous argillite xenoliths. One argillite layer crosses the whole outcrop and dips steeply south. Because the steep dip is so different from that on the south shore, the argillite layer is probably also a xenolith. At the southeast end of Hangman the argillite is folded next to a two-meter, medium-grained dolerite dike. The dike, which strikes S78°E and dips 65°SW, contains scattered one-centimeter feldspar phenocrysts. All the rocks on Hangman, including the dike, show varying degrees of cleavage striking S65°W and dipping about 80°NW. A few rocky islands northeast of the main island, attached by a spit at low tide, are made of coarse dolerite.

Moon Island

Only one area of outcrop is exposed on Moon Island, at the east end under the bridge to Long Island and for about 40 meters back along the south shore. The rocks are similar to the diamictite at

Squantum: a matrix-rich conglomerate of coarse cobbles of granite, quartzite and volcanics in a fine-grained matrix. Very few clasts touch each other, as though they were suspended in the muddy matrix as they were deposited, perhaps as a debris flow (Bailey and Bland, 2001). Bedding is hard to see, but one layer of sandstone near the bridge strikes N51°E and dips 73°SE (fig.33). Cleavage is well developed in some parts of the outcrops, striking approximately due W and dipping 50° to 62°N (fig.34). Crosby (unpub. notebook no.2, 1886) found numerous large green and purple argillite boulders just north of the conglomerate, which suggested to him that argillite underlies the north part of Moon. One can only speculate that diamictite, which is more resistant to erosion than argillite, is also in part responsible for the presence of Long Island, on strike to the NE. Conglomerate was not observed in the Inter-Island Tunnel, but layers of "conglomeratic argillite" were reported in an exploratory borehole north of Long Island.

Slate and Grape Islands

Argillite is exposed most of the way around the perimeter of Slate Island, intruded by a few thin sills. Similar rocks on Grape are limited to an area of outcrop on the south shore, visible from the landing dock, and at low tide off the north point. The argillite is thinly laminated and generally darker gray or even black, compared to that on the outer islands. Bailey (pers. comm., 2009) attributes the black color to finely disseminated pyrite. Cleavage is strongly developed, especially through the south part of Slate Island, where the rock can truly be called a slate (fig.35). Slate was quarried here before the nineteenth century for use in coastal towns. Bedding is often difficult to see due to the strong cleavage, and both bedding and cleavage strike ENE and dip steeply to vertical. Bailey (2005) has measured a total thickness of 290 meters of strata, topping toward the south. He described in great detail primary sedimentary structures such as slump folds (fig.36), mudstone intraclasts and flames, cross-laminations and diamictite layers up to 20 cm thick. One diamictite layer can be seen at the east end of the southern Grape outcrops, and thin siltstone layers are well exposed at low tide on the northern rocks (fig.37). The best place to see faulting is at the northwest point of Slate, where thin dolerite sills are offset by NNW-striking, left-lateral faults.

Glacial striae point S60°E on the rocks north of Grape, but since they are covered at high tide, these scratches could have been caused by a passing boat or other human activity. Near the southwest corner of Slate, striae point in a similar direction, S40°E, but they are also covered at high tide.

Raccoon Island

Most of Raccoon Island is tan-weathering, gray argillite, with slump folds, laminations, starved ripples (fig.38) and graded beds (fig.39) beautifully preserved along the north shore. The beds dip steeply north, but the original topping direction in all cases is toward the south, so the beds have been overturned. Cleavage is well developed in some beds, striking N80°W and dipping 83°NE. There are also good examples of honeycomb weathering (fig.40). One fault toward the west end strikes north and dips 67°E, with slickenlines indicating that the east side moved down and to the north. Crosby (unpub. notebook no.2, 1886) described two thin basalt sills running the length of the island "under the house" which no longer stands.

At low tide on the southwest corner of the island, conglomerate strikes S79°E and dips 32°SW, very differently from the argillite. It is on strike with conglomerate exposed to the west on Huntress Street, Houghs Neck, and it seems likely that a fault passes between the south-dipping conglomerates and the north-dipping argillite. This is probably the same fault as the one observed in the Braintree-Weymouth Tunnel between similar lithologies south of Nut Island (Deere et al., 2004; M.Thompson, pers. comm., 2011). Just to the west on the part of Houghs Neck called Rock Island, basaltic andesite was formerly quarried, overlain to the south by conglomerate with volcanic clasts, sandstone and siltstone (Thompson and Bailey, 2004).

Hingham Harbor Islands
Button Island

The oldest rocks of any in the Boston Harbor islands are exposed on Button Island. The Dedham granite, about 600 million years old, can be seen here and on Rocky Neck at World's End. The granite is a coarse-grained, massive igneous rock made of quartz, microcline and plagioclase, with minor hornblende (fig.41). The outcrop at the south end of the island contains mafic porphyry xenoliths, zones of finer-grained, lighter granite, and epidote veins associated with shear zones (fig.42). At the north end a poor exposure of the granite is littered with conglomerate erratics, dragged here by the glaciers (fig.43). Glacial striae point S28°E, and looking back in the other direction one can see the likely source for the erratics: Sarah, Langlee and Ragged Islands.

Sarah, Langlee and Ragged Islands

These three islands are all very similar, made of conglomerate with thinner layers of sandstone and argillite, all dipping from 32° to 42°S. The flat surfaces tilted into the water along the south shores are bedding planes. The clasts in the conglomerate are mostly well rounded and consist of either volcanics or Dedham granite (fig.44). One basalt sill and one dolerite dike strike parallel to bedding on Langlee. The most interesting rocks lie along the north sides of both Ragged and Sarah, where sandstone dips south beneath the conglomerate (fig.45). Troughs and cross beds indicate that the layers have not been overturned. The sandstone contains isolated round clasts and thin interbeds of pebbles, and on Ragged it includes angular fragments of purplish argillite up to 30 cm across (fig.46). It seems that a fault must pass between Ragged and Sarah, because the layers are offset by about 20 meters.

Worlds End

Geology classes from Boston area colleges and universities have been coming for many years to Rocky Neck at World's End in Hingham to map the interesting pattern of tilted fault blocks. Bailey and Bland (2001) describe how Dedham Granite forms the southern end of the neck, with patches here and there of reddish arkosic sandstone and roundstone conglomerate resting nonconformably on the granite. North of the first NW-striking normal fault a sequence of conglomerate, dark volcanics (fig.47) and angular diamictite lies on top of the granite, all tilted gently southeast. A second down-dropped block forms the tip of Rocky Neck, and this block contains a different sequence of mafic volcanics (possibly lahar deposits), thin conglomerate and feldspathic litharenite, amygdaloidal mafic volcanic flows, and polymictic roundstone conglomerate somewhat like that on the Hingham Harbor Islands; again, all layers are tilted about 15° SE. These materials were likely deposited into rift basins even as faults continued to form and deepen the graben valleys. One line of evidence in support of this model is that arkose fills joints in the granite, indicating that they were open prior to deposition (Bailey and Bland, 2001). They describe the setting as "a rugged, tectonically active, basin … Basaltic and andesitic flows, probably both subaerial and submarine, were cannibalized by erosion to produce clasts while tectonic and volcanic processes were [still] active."

Miscellaneous

Irving Crosby (1936) mentioned a dolerite sill off the south point of Lovells Island at low tide. Could he have meant something along the west end of Great Brewster Spit? This is an area where we have zero bedrock data, and an orientation of layering would be very useful and warrants a visit on a spring tide. Crosby (unpub. notebook no.4, no date) mentions "dark green fissile diabase" on Globe or Cabbage Rock, which so far we have not identified on any maps. The rock is 50 feet long and 25 feet high.

Crosby (1893) mentioned sandstone and fine conglomerate at Harding Ledge, east of Nantasket. He noted that "examinations were unsatisfactory on account of the surf", so a visit on a spring tide would be necessary. On a map Crosby showed the sandstone extending west through Strawberry Ledge, Strawberry Hill and Bumkin Island. Although no bedrock is exposed in these places, he speculated in an unpublished notebook (no.5, 1888) that similar more resistant rocks might hold up these hills. In the same notebook Crosby wrote that Toddy Rocks, north of Hull, are "bright green slate" with cleavage at N70°E, 85°NW and beds dipping 15° N. We visited purplish argillite on the south shore

of Hull, also with steep cleavage and very gently dipping beds.

At low tide it appears that Pig Rock, east of Nut Island, is simply a pile of loose blocks. But are they resting on bedrock? Some scuba diving might tell us the answer, but one must be wary of strong wakes produced by passing ferries.

Summary of Geology by Island

Island	Rock Type
Button	granite
Calf	argillite intruded by dolerite sills and dikes (one E-W)
Grape	argillite intruded by dolerite and felsic sills
Graves	dolerite sill cut by E-W dike
Green	dolerite sill with minor argillite; breccia zone at S end
Hangman	argillite intruded by dolerite sills and dikes
Langlee	conglomerate and sandstone intruded by dolerite sills
Little Brewster	argillite intruded by dolerite sills
Little Calf	dolerite
Middle Brewster	dominantly dolerite sills with argillite along SE shore
Moon	diamictic conglomerate at east end under bridge
Outer Brewster	dominantly dolerite sills with argillite along SE shore
Quarantine Rocks	argillite with at least one dolerite sill
Raccoon	argillite and sandstone; conglomerate SW corner
Rainsford	argillite; minor felsic sills
Ragged	conglomerate and sandstone
Roaring Bulls	dolerite
Sarah	conglomerate and sandstone
Shag Rocks	dolerite
Slate	argillite intruded by dolerite and felsic sills
Worlds End	granite overlain by conglomerate and volcanics

Unconfirmed Bedrock

Great Brewster Spit - - rocks at low tide - - no mention in the literature	
Harding Ledge	Crosby, W.O. (1893): sandstone and fine conglomerate
Lovells*	Crosby, I.B. (1936): dolerite sill off S point at low tide
Pig Rock	quarried blocks resting on what?
Sunken Ledge	Crosby, W.O. (1880): brownish slate with pebbles

No Reported Bedrock

Bumpkin, Deer, Gallops, Georges, Long, Nixes Mate, Nut, Peddocks, Sheep, Snake, Spectacle, and Thompson

References

Bailey, R.H., 2005, Stratigraphy and depositional setting of Neoproterozoic strata on southern Boston Harbor islands, Boston Bay Group, Massachusetts, Geological Society of America Abstracts with Programs, v. 37, no. 1, p. 71.

Bailey, R.H., W.A. Newman and A. Genes, 1976, Geology of the Squantum “Tillite”, *in* Cameron, B., ed., Geology of Southeastern New England: A guidebook for field trips to the Boston area and

vicinity, 68th Annual Meeting, New England Intercollegiate Geological Conference, p. 92-106.

Bailey, R.H. and M.E. Ross, 1993, Geology of East Point, Nahant, Massachusetts, *in* Cheney, J.T. and J.C. Hepburn, eds., Field Trip Guidebook for the Northeastern United States, 1993 Geological Society of America Annual Meeting, Boston, Contribution No. 67, University of Massachusetts, Amherst, MA, p. Y1-Y24.

Bailey, R.H. and B.H. Bland, 2001, Recent developments in the study of the Boston Bay Group, *in* West, D.P., Jr. and R.H. Bailey, Guidebook for Geological Field Trips in New England, 2001 Annual Meeting of the Geological Society of America, Trip 23, p. U1-U23.

Barosh, P. and D. Woodhouse, 1991, Geology of Boston, Massachusetts, United States of America, Bulletin of the Association of Engineering Geologists, v. 28, no. 4, p. 375-512.

Billings, M.P., 1975, Geology of the North Metropolitan Relief Tunnel, Greater Boston, Massachusetts, Journal of the Boston Society of Civil Engineers Section, American Society of Civil Engineers, v. 62, p. 115-135.

Billings, M.P., 1976, Bedrock Geology of the Boston Basin, *in* Cameron, B., ed., Geology of Southeastern New England: A guidebook for field trips to the Boston area and vicinity, 68th Annual Meeting, New England Intercollegiate Geological Conference, p. 28-45.

Cardoza, K.D., J.C. Hepburn and R. Hon, 1990, Geochemical constraints on the paleotectonic setting of two late Proterozoic mafic volcanic suites, Boston-Avalon zones, eastern Massachusetts, *in* Socci, A.D., J.W. Skehan and G.W. Smith, eds., Geology of the composite Avalon terrane of southern New England, Geological Society of America Special Paper 245, p. 113-131.

Clapp, C.H. and J. Daniels, 1904, Geological Map of Rock Island, unpublished manuscript map, MIT archives, 1:1800.

Clarke, E.C., 1885, Main Drainage Works of the City of Boston, Rockwell and Churchill, Boston, 197 p.

Crosby, I.B., 1936, Report of the special committee on the investigation of the discharge of sewage into Boston Harbor and its tributaries, Massachusetts House Report no.1600.

Crosby, W.O., 1880, Contributions to the geology of eastern Massachusetts, Boston Society of Natural History, Occasional Papers III, p. 181-276.

Crosby, W.O., 1888, Geology of the outer islands of Boston Harbor, Boston Society of Natural History, Proceedings, p. 450-457.

Crosby, W.O., 1889, Physical History of the Boston Basin, Boston Society of Natural History, Lowell Free Courses 1889-1890, 22 p.

Crosby, W.O., 1893, Geology of the Boston Basin, Boston Society of Natural History, Occasional Papers IV, v.1, part 1 Nantasket and Cohasset, p. 1-177.

Crosby, W.O., 1894, Geology of the Boston Basin, Boston Society of Natural History, Occasional Papers IV, v.1, part 2 Hingham, p. 179-288.

Crosby, W.O., 1885-1901, unpublished field notebooks, Manuscript Collection M68, box 2, folders 18 & 34, Massachusetts Institute of Technology Libraries Archive.

Dana, J.F. and S.L. Dana, 1818, Outlines of the mineralogy and geology of Boston and its vicinity, with a geological map, Cummings and Hilliard, Cambridge.

Deere, D.W., J. Kantola and T. Davidson, 2004, Conditions encountered in the construction of the Braintree-Weymouth tunnel project, Boston, Massachusetts, *in* Ozdemir, L., ed., North American Tunneling 2004, Balkema Pub., London, p. 411-420.

Dott, R.H., Jr., 1961, Squantum "Tillite", Massachusetts: Evidence of glaciation or subaqueous mass movements?, Geological Society of America Bulletin, v. 72, p. 1289-1306.

Emerson, B.K., 1917, Geology of Massachusetts and Rhode Island, United States Geological Survey Bulletin 596, 289 p.

GZA Environmental, 1995, File 12427, MWRA CP 151; MWRA Call # DIG 29 Rpt - Interisland Tunnel unpublished data

Kaye, C.A., 1980, Bedrock Geologic Maps of the Boston North, Boston South and Newton Quadrangles, Massachusetts, United States Geological Survey Miscellaneous Field Series MF-1241, 1:24,000.

LaForge, L., 1932, Geology of the Boston area, Massachusetts, United States Geological Survey Bulletin 839, 105 p.

Lenk, C., P.K. Strother, C.A. Kaye and E.S. Barghoorn, 1982, Precambrian age of the Boston Basin: New evidence from microfossils, Science, v. 216, p. 619-120.

Metcalf & Eddy, 1989, 1990,Unpublished reports to the Massachusetts Water Resources Authority.

McHone, J.G., 1978, Distribution, orientations, and ages of mafic dikes in central New England, Geological Society of America Bulletin, v. 89, p. 1645-1655.

Morell, K.D., M.D. Thompson and J. Kaplan, 2004, Structural history of the Cambridge Argillite: Insights from tunnels near Deer Island, Boston Harbor, Massachusetts, Geological Society of America Abstracts with Programs, v. 36, no. 2, p. 138.

Nance, R.D., 1990, Arc-platform transitions in the Avalon terrane, *in* Socci, A.D., J.W. Skehan and G.W. Smith, eds., Geology of the composite Avalon terrane of southern New England, Geological Society of America Special Paper 245, p. 1-11.

Rahm, D.A. 1962, Geology of the Main Drainage Tunnel, Boston, Massachusetts, Journal of the Boston Society of Civil Engineers, v. 49, p. 319-368.

Ross, M.E., 1990, Mafic dikes of the Avalon Boston terrane, Massachusetts: *in* Socci, A.D., J.W. Skehan and G.W. Smith, eds., Geology of the composite Avalon terrane of Southern New England, Geological Society of America Special Paper 245, p. 133-153.

Sarson, J. 1998, A petrographic and geochemical interpretation of the intrusion of a differentiated sill complex on Calf Island in the Boston Harbor, Massachusetts, Senior thesis, Wellesley College, 62 p.

Sayles, R.W., 1914, The Squantum tillite, Museum of Comparative Zoology Bulletin, v.56, Geology Series v. 10, p. 141-175.

Skehan, J.W. and D.P. Murray, 1980, A model for the evolution of the eastern margin of the northern Appalachians, *in* Wones, D.R., ed., The Caledonides in the USA, Proceedings, International Geological Correlation Program, Project 27, Blacksburg, Virginia Polytechnic Institute and State University memoir 2, p. 67-72.

Snow, E.R., 1971, The Islands of Boston Harbor, 1630-1971, Dodd, Mead & Co., New York, 274 p.

Socci, A.D. and G.W. Smith, 1990, Stratigraphic implications of facies within the Boston Basin, *in* Socci, A.D., J.W. Skehan and G.W. Smith, eds., Geology of the composite Avalon terrane of southern New England, Geological Society of America Special Paper 245, p. 55-74.

Thompson, M.D. and R.H. Bailey, 2004, Ungrouping the Boston Bay Group, *in* Murray, D.P., ed., Guidebook to Field Trips in Rhode Island and adjacent regions of Connecticut and Massachusetts, 90th Annual Meeting, New England Intercollegiate Geological Conference, Trip B1, p. 1-21.

Thompson, M.D., 1983, Late Proterozoic stratigraphy and structure in the Avalonian magmatic arc, southwest of Boston, Massachusetts, American Journal of Science, v. 293, p. 725-743.

Thompson, M.D., A.M. Grunow, and J. Ramezani, 2010, Cambro-Ordovician paleogeography of the Southeastern New England Avalon Zone: Implications for Gondwana breakup, Geological Society of America Bulletin, v. 122, p. 76-88.

Thompson, M.D., A.M. Grunow and J. Ramezani, 2007, Late Neoproterozoic paleogeography of the Southeastern New England Avalon Zone: Insights from U-Pb geochronology and paleomagnetism, Geological Society of America Bulletin, v. 119, no. 5/6, p. 681-696.

Zen, E-an, ed., 1983, Bedrock geologic map of Massachusetts, United States Geological Survey, 1:250,000.

Acknowledgements

The authors would like to thank Marty Ross and Dick Bailey of Northeastern University and Meg Thompson of Wellesley College for extensive collaboration and discussion. Natalie Collins (National Park Service volunteer) and Thelma Thompson (University of New Hampshire) helped collect data several days in the field. Paul Daly and Russ Bowles provided transport to many of the islands via UMass/ Boston's landing craft. Steve Mabee, Massachusetts' State Geologist,in addition to providing invaluable administrative support, lent the use of his dinghy, without which we could not have reached the rockiest islands. We thank the staff at the Outward Bound facilities on Thompson Island for hospitality during the field stage of the project.Marc Albert (NPS) was instrumental in facilitating the initial field logistics of this project. Thelma Thompson made helpful suggestions for improving the text. Jütta Hager and Mario Carnevale (Hager Geosciences), Rick Ponti (AECOM), David Woodhouse (AEG), Pat Barosh (AEG), Rebecca Kenney (MWRA), and Bill Levy (MWRA) were indispensable in helping us both obtain and interpret geotechnical data for Boston Harbor. Chris Koteas (MGS) and Michael Vollinger (UMass Amherst) provided expert technical and logistical assistance with geochemical sample preparation. Lastly, we thank colleagues at UMass/Amherst and UNH for their interest and insight, especially Don Wise, Joel Johnson and Wally Bothner.

Report Figures

Below is a table of figures present in the bedrock geology report. No additional information pertaining to Station # was provided with the source data.

Fig #	Station #	Caption
1	5-4-10-4	Diamictic conglomerate at Chapel Rocks, Squantum.
2	C18	Dolerite pillows surrounded by felsite, Calf Island.
3	6/25/2010	Old granite breakwater and view of Boston from Lovells Island.
4		Cliff of glacial till, Great Brewster Island, viewed from Calf Island.
5	LB17	Groove casts on bedding in argillite, Little Brewster Island.
6	LB8A	Grayish argillite between two brown dolerite sills, Boston Light, Little Brewster. Photo by J.Kopera.
7	LB3B	Argillite fragments in felsite below tan-weathering dolerite sill, Little Brewster.
8	LB3	Folded argillite and dolerite sill, north shore, Little Brewster Island.
9	MB10B	Soft sediment structures in argillite, Middle Brewster Island. 10cm pencil for scale.
9A	MB31	Coarse, pegmatitic dolerite on Middle Brewster Island. This location was sampled for potential radiometric dating.
10	MB35	Glacial grooves and striations on Middle Brewster Island.
11	MB27	Domes formed by curved joints, north shore, Middle Brewster Island.
12	MB20B	North dipping dolerite sills on Middle Brewster, looking across the Flying Place to Outer Brewster Island.
13	OB16	Basalt sill with chilled margins and vesicular center intruding dolerite, Outer Brewster Island.

14	OB10	Dan Solway and park volunteer Natalie Collins measure joints in north-dipping dolerite sills, north shore of Outer Brewster Island. Graves Light and container vessel in distance.
15	E of OB15	Open anticline on south shore of Outer Brewster Island.
16	OB1C	Fault north of the landing cove on Outer Brewster Island. View toward the southeast.
17	C3B	Vertical dolerite dike cutting dolerite and argillite, northwest shore, Calf Island. View toward the east.
18	C10	Rugged headland formed by E-W dike on northeast part of Calf Island. Note person for scale, right of center. Outer Brewster in distance to left.
19	C11	Argillite overlain by dolerite sill in cliff south of landing cove, Calf Island.
20	C12	Layered sill south of landing cove, Calf Island.
21	C13	Brown-weathering picritic dolerite sill with chilled margin overlying greenish sill, Calf Island.
22	C14	Felsite dike about 50cm thick intrudes dolerite from the underlying argillite in the cliff below the “cottage” ruins.
23	C17E	Foliated diabase at the south tip of Calf Island.
24	C25	Dan Solway measures bedding on small anticline plunging NE, east shore, Calf Island.
25	G9	Breccia on Green Island. Note the variety of clast compositions and shapes.
26	G9	Jigsaw pattern of angular clasts in felsite breccia on Green Island.
27	Graves S dike zoom	E-W dike cutting dolerite sill, south end of The Graves.
28	R3	Isoclinal slump folds in argillite on Rainsford Island. Cleavage associated with younger, open fold dips NW across the isoclines.

29	R1	Cleavage parallel to open folds in argillite, Rainsford Island. View WSW toward Moon and Squantum in distance.
30	R7	Tan weathering sill parallel to NW-dipping argillite beds, southeast arm of Rainsford Island. Cleavage dips steeply NW.
31	R13	Concretions along east shore of Rainsford Island.
32	R8	Quarantine Rocks from Rainsford Island.
33	Moon 1	Sandstone bed in diamictite, dipping south. View is toward the north, under the bridge from Moon Island to Long Island.
34	Moon 1	North-dipping cleavage in diamictite, Moon Island.
35	Slate 13	Slaty cleavage near old slate quarry, south shore of Slate Island.
36	Slate 9a	Slump folds along east shore of Slate Island.
37	G5	Siltstone layers, northeast corner of Grape Island.
38	Rac5	Starved ripple marks, north shore of Raccoon Island. Quarter for scale.
39	Rac6	Graded beds top south (top of photo) on Raccoon Island. Quarter for scale.
40	Rac5	Honeycomb weathering due to seawater salt, Raccoon Island. Quarter for scale.
41	B1	Dedham Granite, south shore Button Island.
42	B1	Epidote veins in granite, Button Island. Quarter for scale.
43	B2	Erratics on bedrock, north shore of Button Island.
44	Langlee 3	Roundstone conglomerate, Langlee Island. Note variety of clasts.
45	Sarah 1	Interbedded sandstone and conglomerate, east end of Sarah Island.

46	Ragged 3B	Angular purplish argillite cobble in conglomerate, north shore of Ragged Island.
47		Melaphyric volcanics at Rocky Neck, Worlds End, Hingham.

Figure 1: Diamictic conglomerate at Chapel Rocks, Squantum



Figure 2: Dolerite pillows surrounded by felsite, Calf Island



Figure 3: Old granite breakwater and view of Boston from Lovells Island



Figure 4: Cliff of glacial till, Great Brewster Island, viewed from Calf Island



Figure 5: Groove casts on bedding in argillite, Little Brewster Island



Figure 6: Grayish argillite between two brown dolerite sills, Boston Light, Little Brewster



** Photo by J.Kopera.

Figure 7: Argillite fragments in felsite below tan-weathering dolerite sill, Little Brewster



Figure 8: Folded argillite and dolerite sill, north shore, Little Brewster Island



Figure 9: Soft sediment structures in argillite, Middle Brewster Island



** 10cm pencil for scale.

Figure 9a: Coarse, pegmatitic dolerite on Middle Brewster Island



** This location was sampled for potential radiometric dating.

Figure 10: Glacial grooves and striations on Middle Brewster Island



Figure 11: Domes formed by curved joints, north shore, Middle Brewster Island



Figure 12: North dipping dolerite sills on Middle Brewster, looking across the Flying Place to Outer Brewster Island



Figure 13: Basalt sill with chilled margins and vesicular center intruding dolerite, Outer Brewster Island

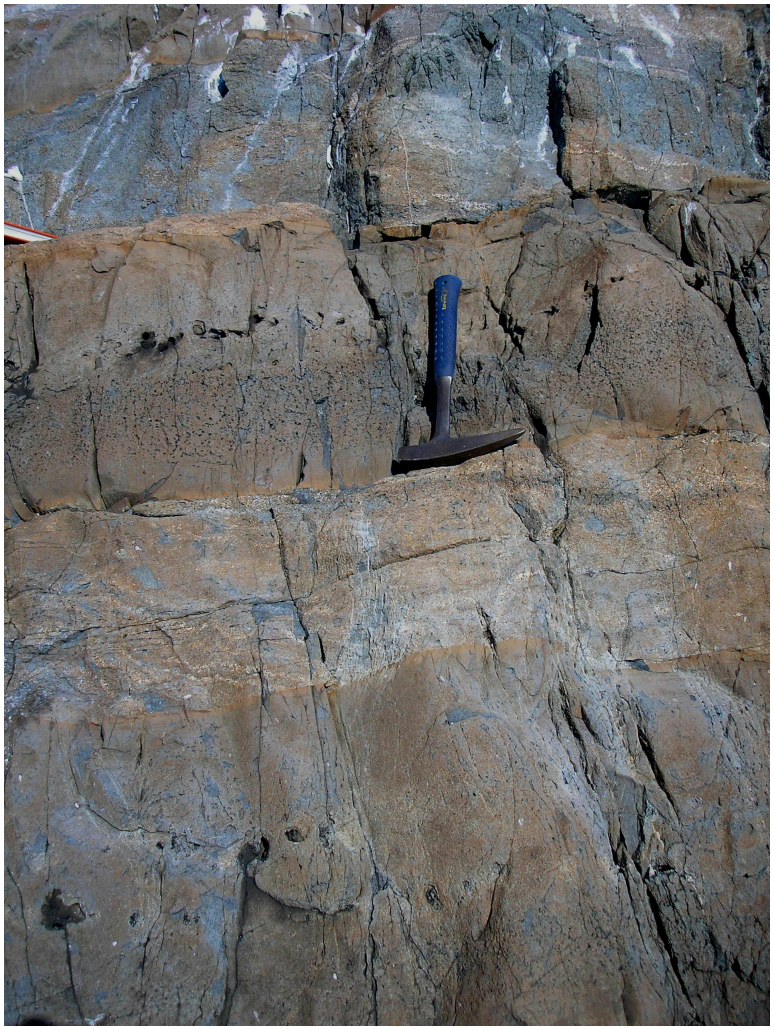


Figure 14: Dan Solway and park volunteer Natalie Collins measure joints in north-dipping dolerite sills, north shore of Outer Brewster Island. Graves Light and container vessel in distance



Figure 15: Open anticline on south shore of Outer Brewster Island



Figure 16: Fault north of the landing cove on Outer Brewster Island



** View toward the southeast.

Figure 17: Vertical dolerite dike cutting dolerite and argillite, northwest shore, Calf Island



** View toward the east.

Figure 18: Rugged headland formed by E-W dike on northeast part of Calf Island



** Note person for scale, right of center. Outer Brewster in distance to left.

Figure 19: Argillite overlain by dolerite sill in cliff south of landing cove, Calf Island



Figure 20: Layered sill south of landing cove, Calf Island



Figure 21: Brown-weathering picritic dolerite sill with chilled margin overlying greenish sill, Calf Island



Figure 22: Felsite dike about 50cm thick intrudes dolerite from the underlying argillite in the cliff below the "cottage" ruins



Figure 23: Foliated diabase at the south tip of Calf Island



Figure 24: Dan Solway measures bedding on small anticline plunging NE, east shore, Calf Island



Figure 25: Breccia on Green Island



** Note the variety of clast compositions and shapes.

Figure 26: Jigsaw pattern of angular clasts in felsite breccia on Green Island

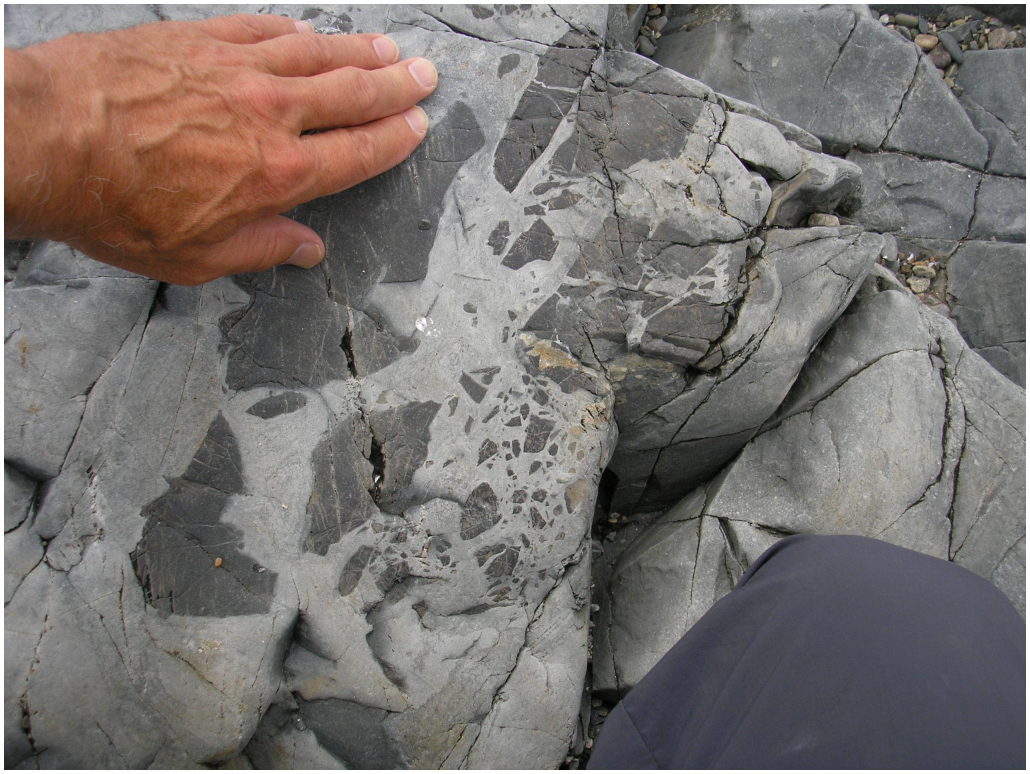


Figure 27: E-W dike cutting dolerite sill, south end of The Graves



Figure 28: Isoclinal slump folds in argillite on Rainsford Island



** Cleavage associated with younger, open fold dips NW across the isoclines.

Figure 29: Cleavage parallel to open folds in argillite, Rainsford Island



View WSW toward Moon and Squantum in distance.

Figure 30: Tan weathering sill parallel to NW-dipping argillite beds, southeast arm of Rainsford Island



** Cleavage dips steeply NW.

Figure 31: Concretions along east shore of Rainsford Island



Figure 32: Quarantine Rocks from Rainsford Island



Figure 33: Sandstone bed in diamictite, dipping south



**View is toward the north, under the bridge from Moon Island to Long Island

Figure 34: North-dipping cleavage in diamictite, Moon Island



Figure 35: Slaty cleavage near old slate quarry, south shore of Slate Island



Figure 36: Slump folds along east shore of Slate Island

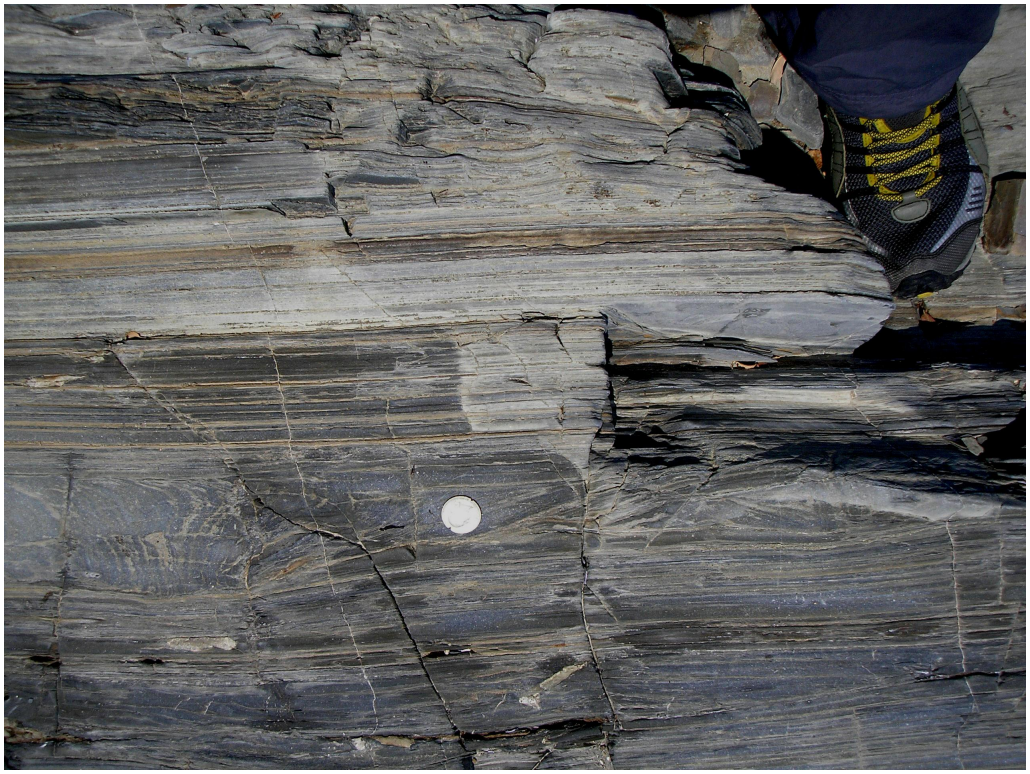
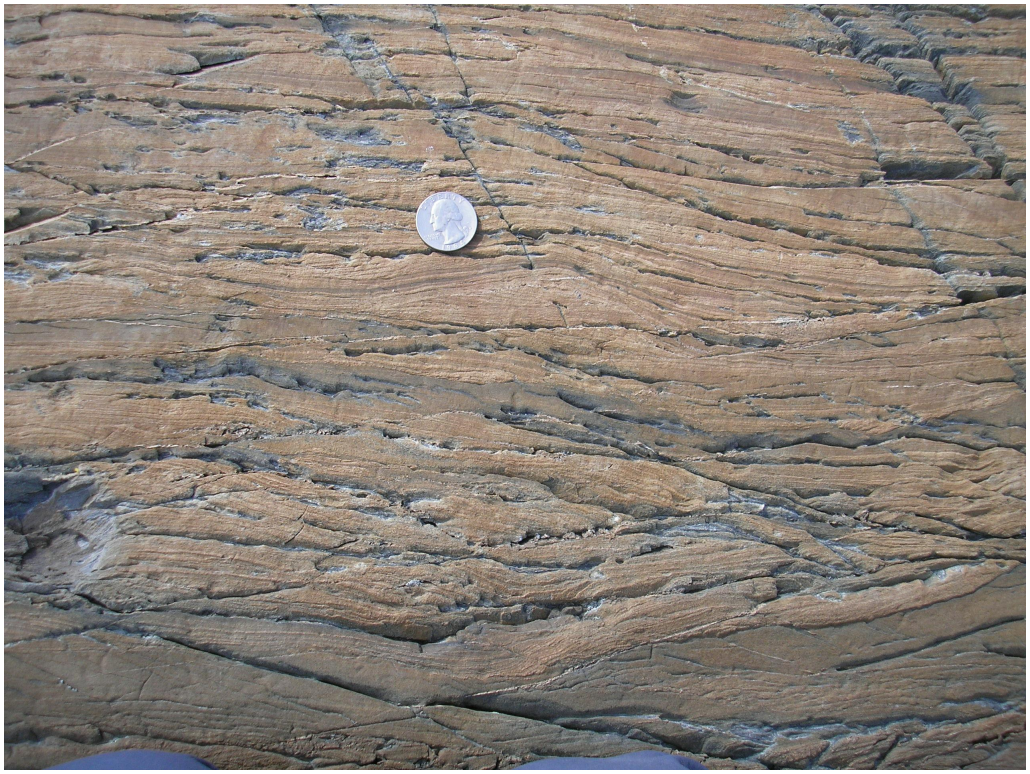


Figure 37: Siltstone layers, northeast corner of Grape Island



Figure 38: Starved ripple marks, north shore of Raccoon Island



** Quarter for scale.

Figure 39: Graded beds top south (top of photo) on Raccoon Island



** Quarter for scale.

Figure 40: Honeycomb weathering due to seawater salt, Raccoon Island



** Quarter for scale.

Figure 41: Dedham Granite, south shore Button Island



Figure 42: Epidote veins in granite, Button Island



** Quarter for scale.

Figure 43: Erratics on bedrock, north shore of Button Island



Figure 44: Roundstone conglomerate, Langlee Island



**Note variety of clasts.

Figure 45: Interbedded sandstone and conglomerate, east end of Sarah Island



Figure 46: Angular purplish argillite cobble in conglomerate, north shore of Ragged Island



Figure 47: Melaphyric volcanics at Rocky Neck, Worlds End, Hingham

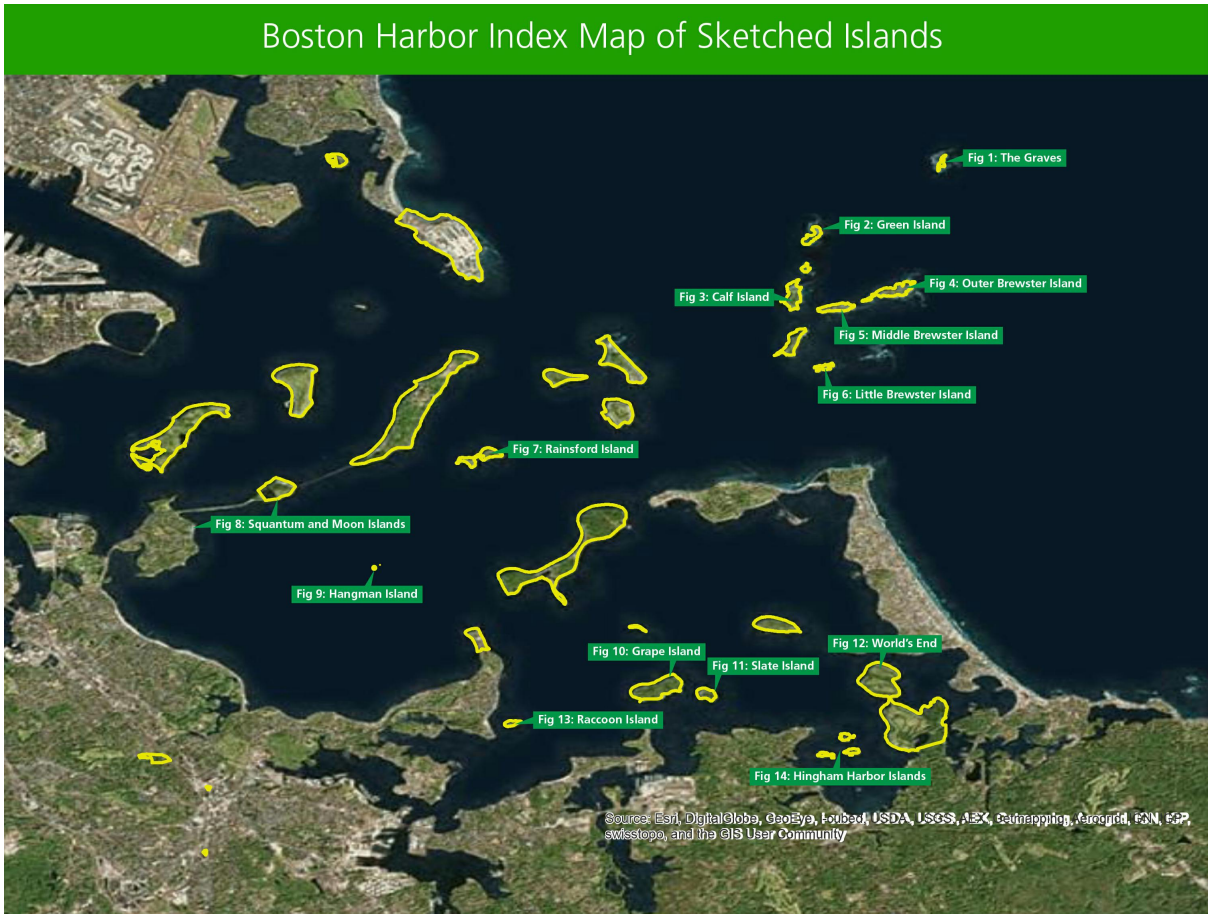


Bedrock Sketch Figures

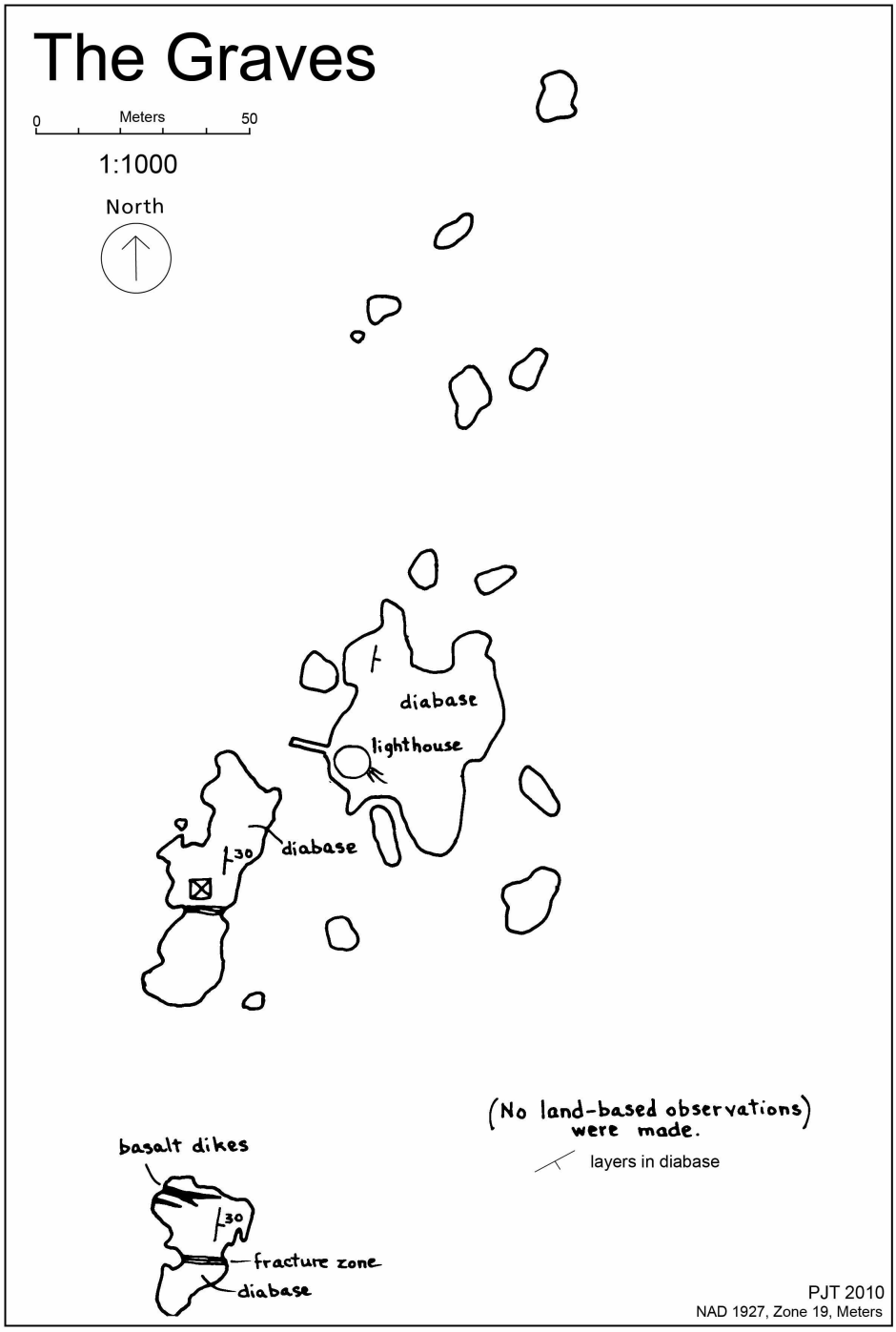
The following are geologic sketches of islands within Boston Harbor Islands National Recreation Area that were included with the Massachusetts Geological Survey Bedrock Geology Map. The graphics we cleaned-up by the GRI by adding a standard north arrow symbol, rule bar, explanation text, border box and/or island name text.

Index Map of Bedrock Sketch Figures

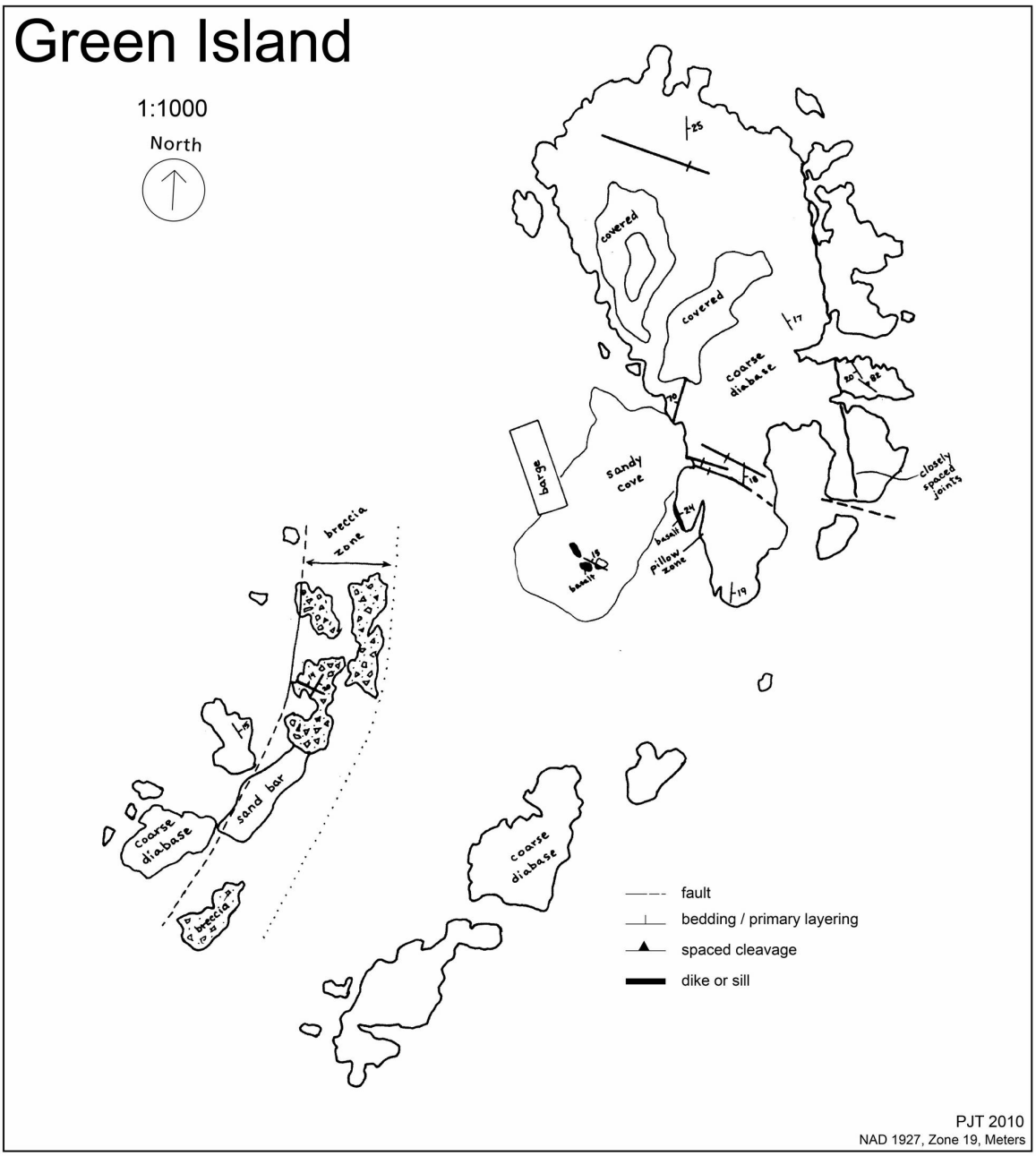
Below is an index map illustrating which islands have a sketch figure. Only those islands identified in the figure (e.g., Fig 1: The Graves) have a sketch figure.



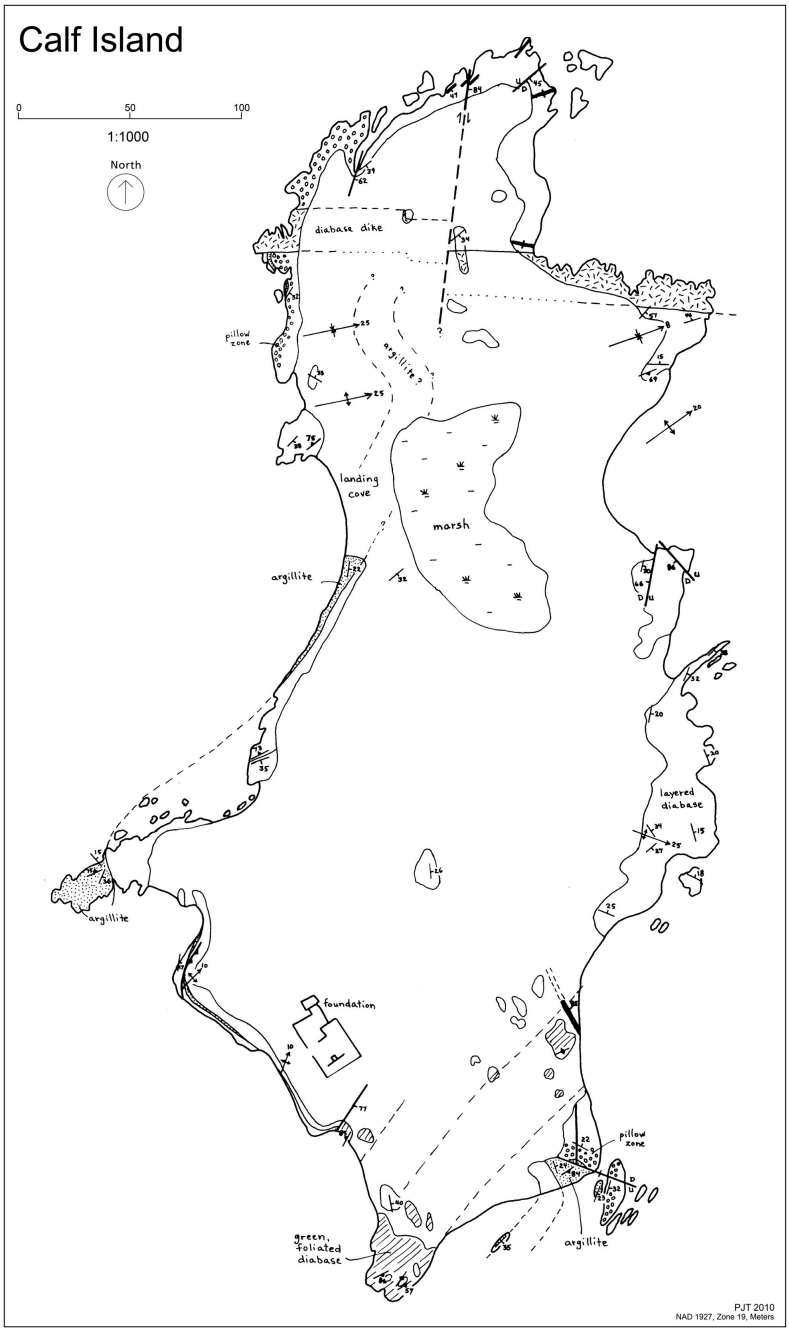
Sketch Figure 1: The Graves



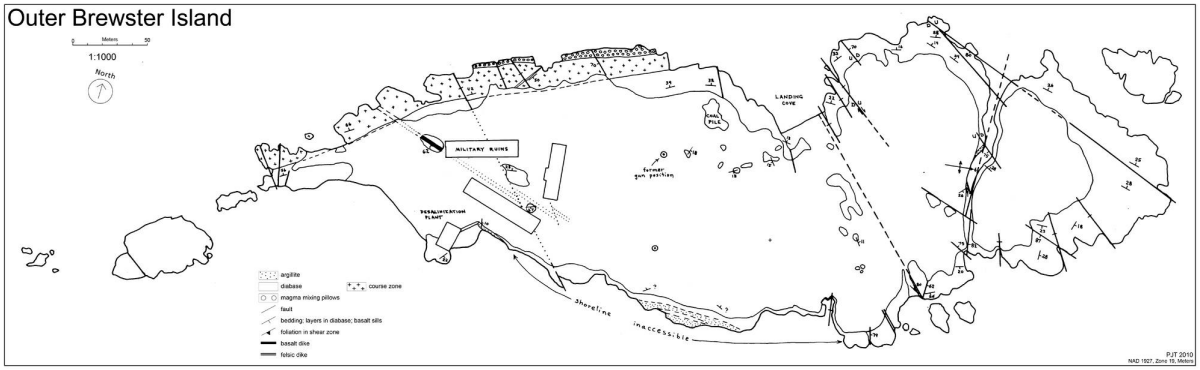
Sketch Figure 2: Green Island



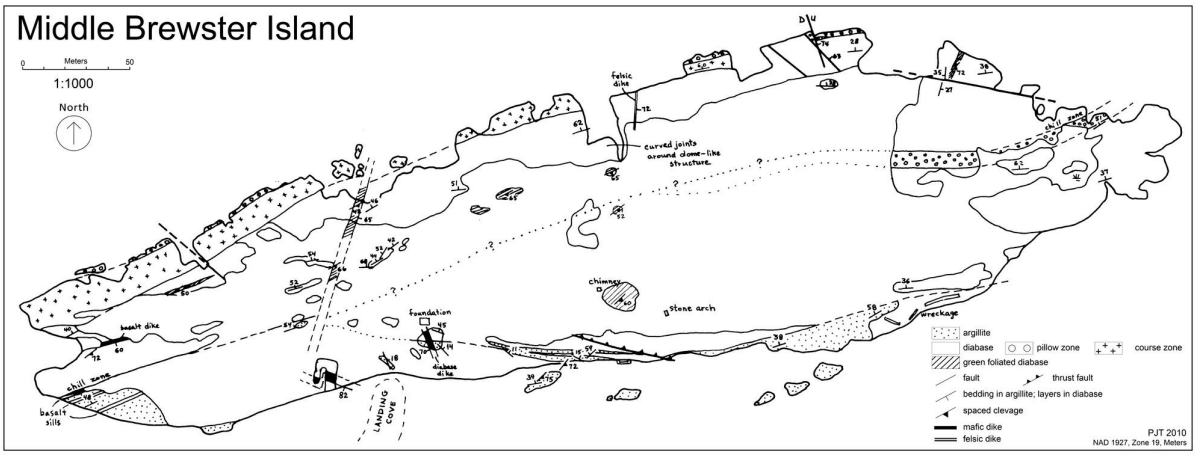
Sketch Figure 3: Calf Island



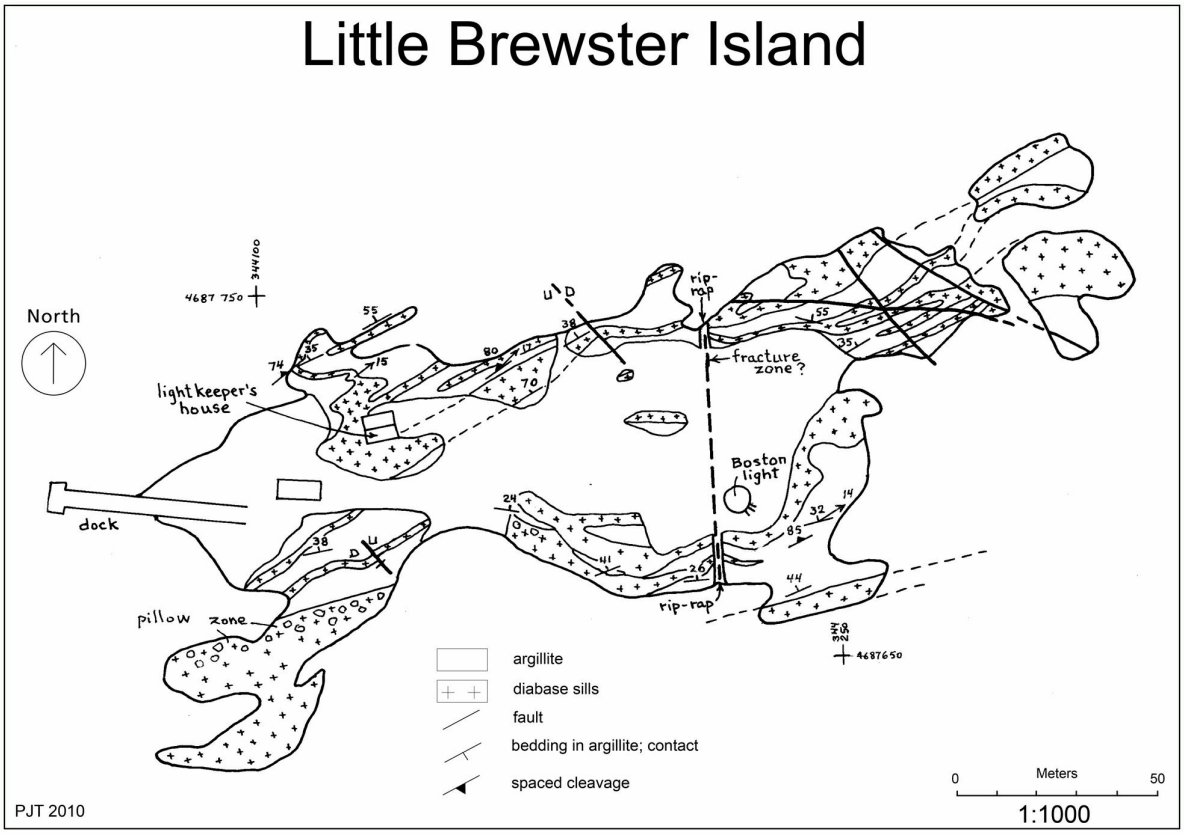
Sketch Figure 4: Outer Brewster Island



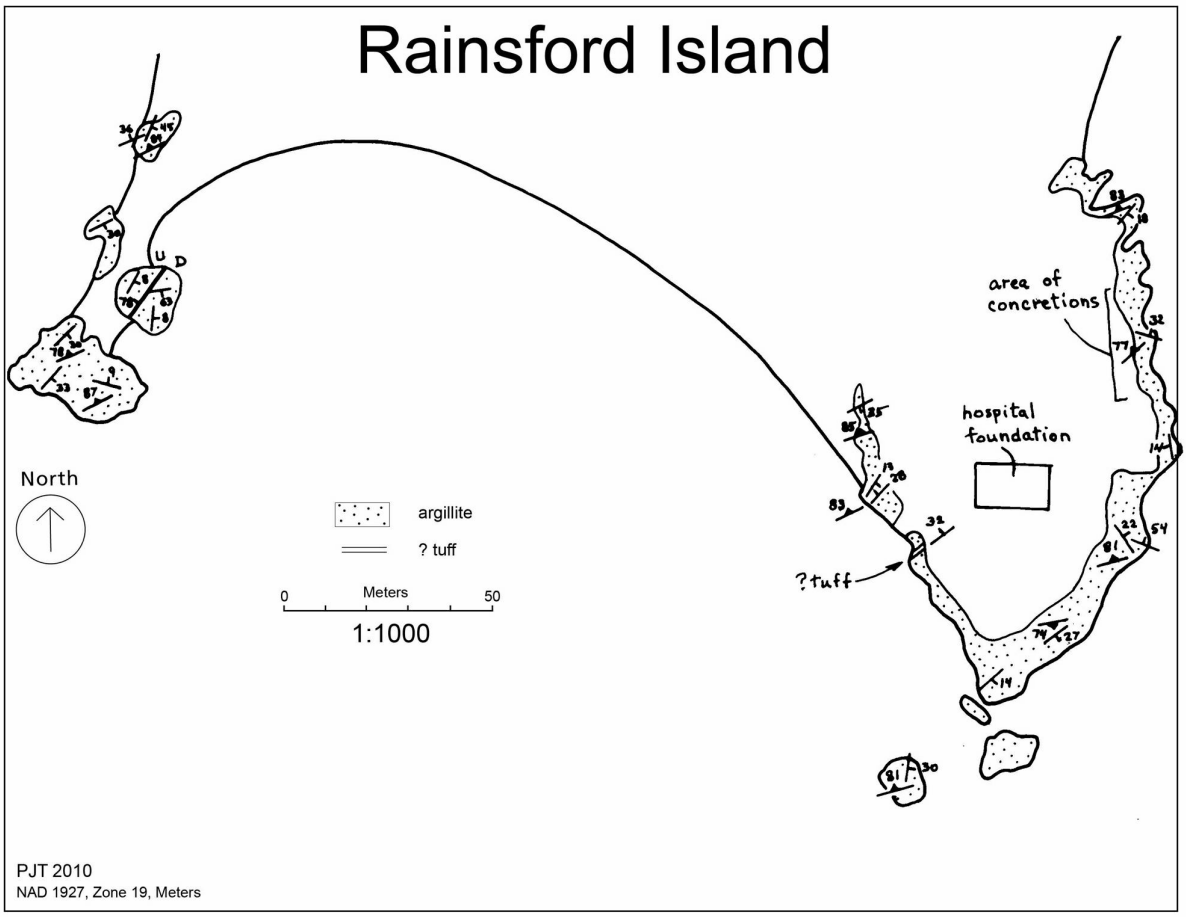
Sketch Figure 5: Middle Brewster Island



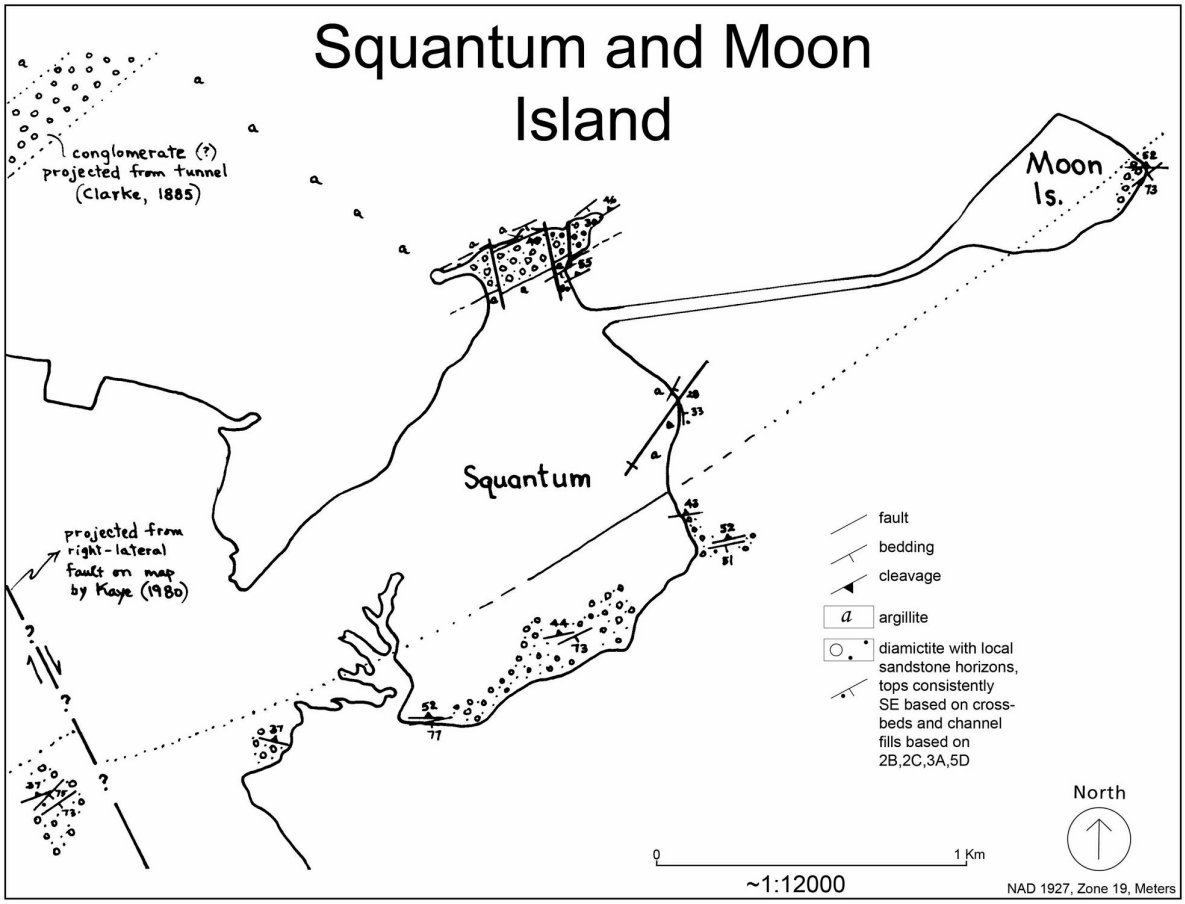
Sketch Figure 6: Little Brewster Island



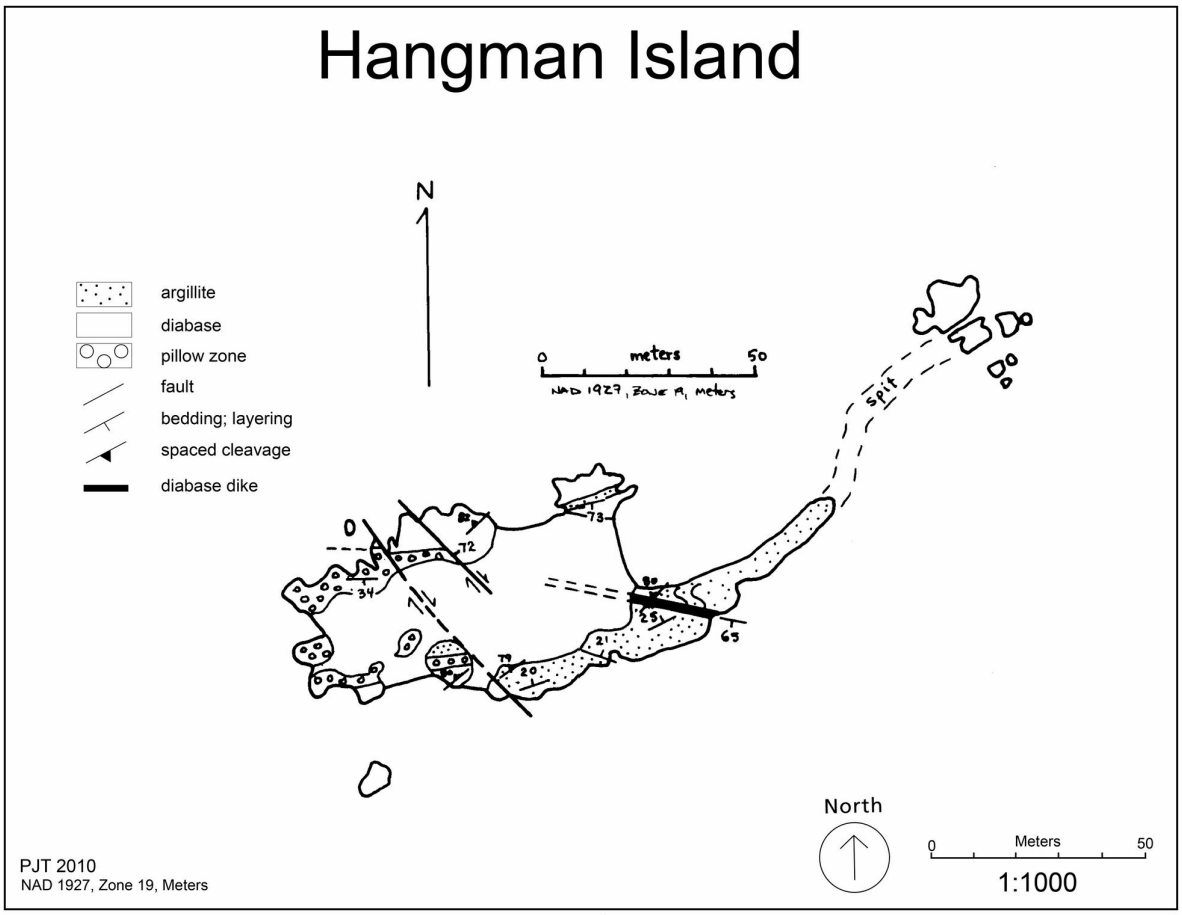
Sketch Figure 7: Rainsford Island



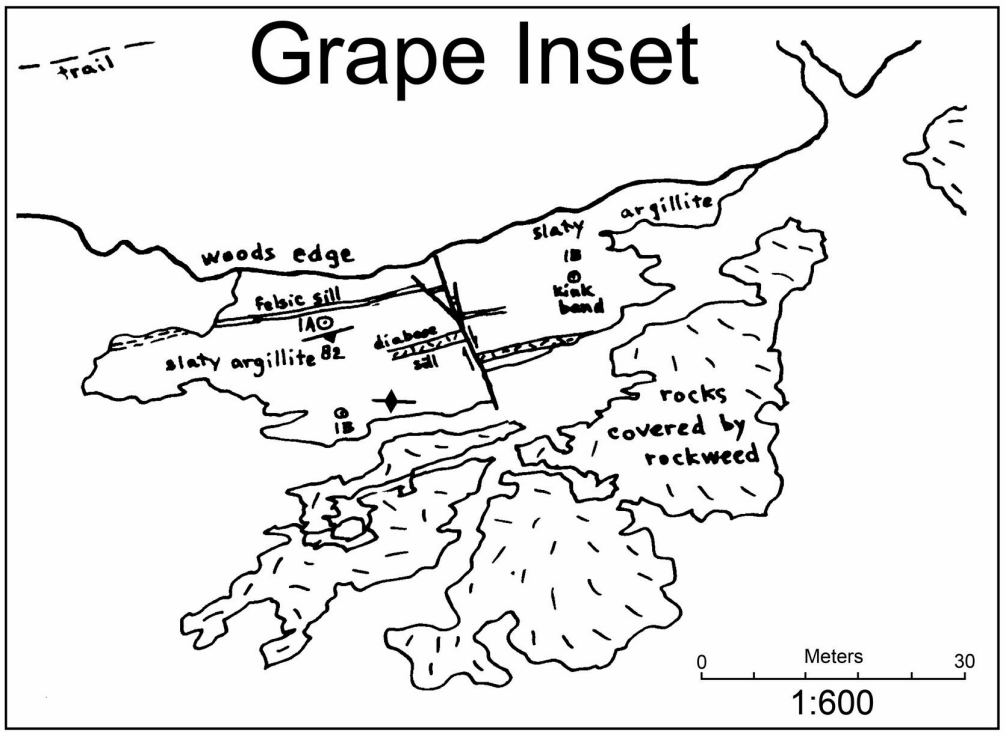
Sketch Figure 8: Squantum and Moon Island



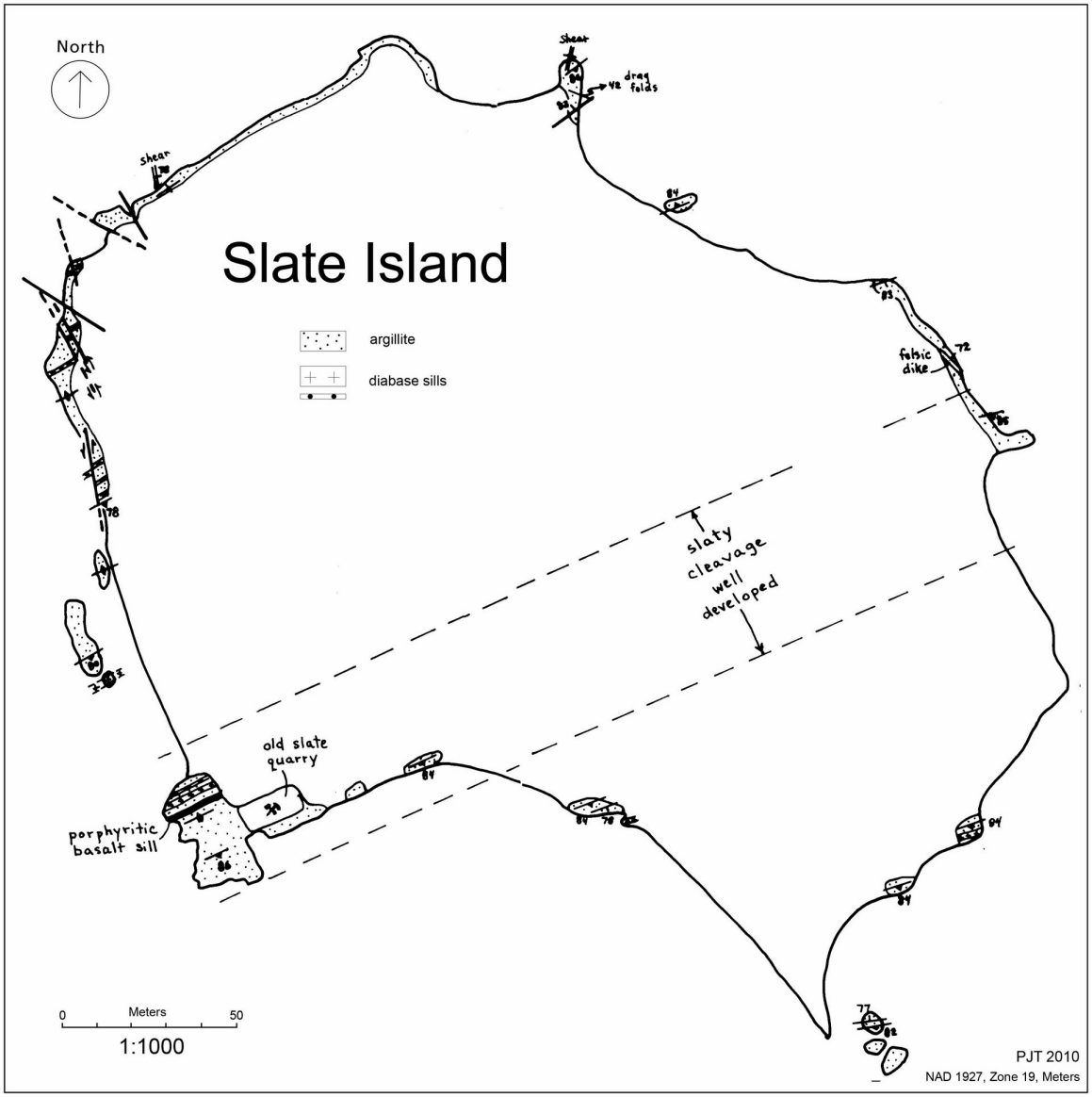
Sketch Figure 9: Hangman Island



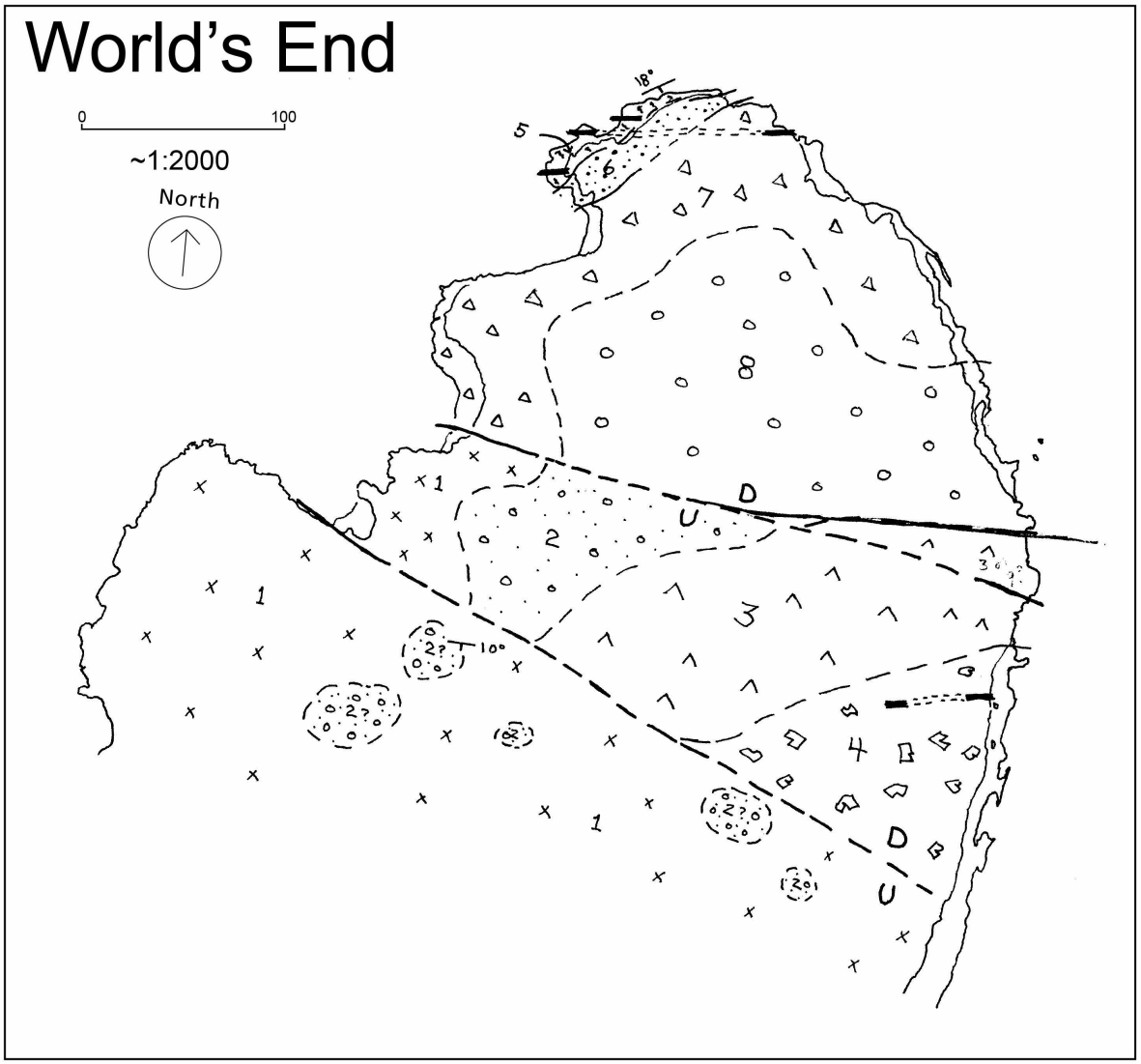
Sketch Figure 10: Grape Island



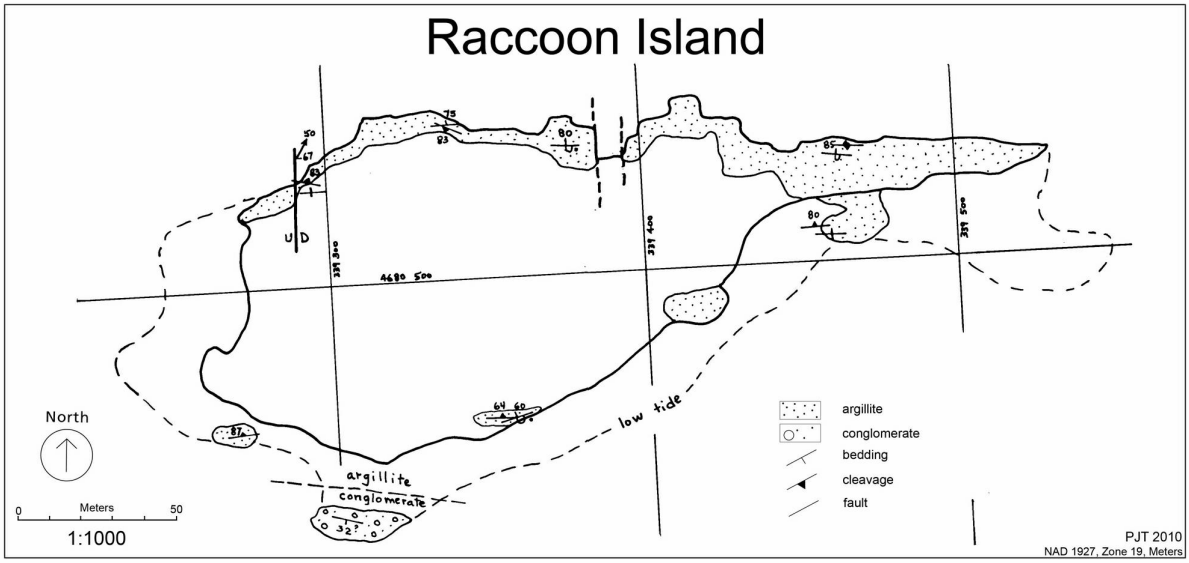
Sketch Figure 11: Slate Island



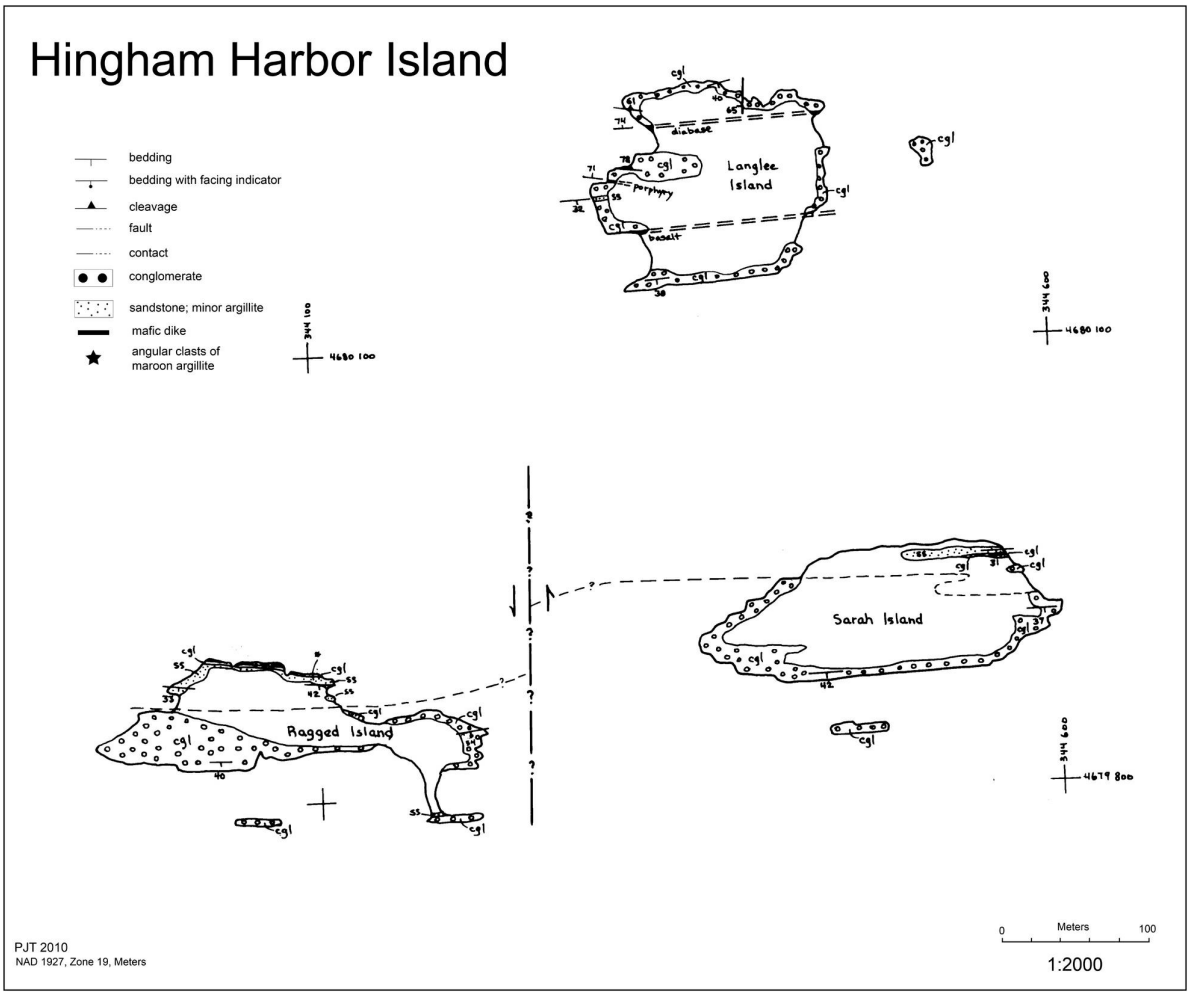
Sketch Figure 12: World's End



Sketch Figure 13: Raccoon Island



Sketch Figure 14: Hingham Harbor Islands



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This document was developed and completed by James Winter, Stephanie O'Meara and Kari Lanphier (Colorado State University) for the NPS Geologic Resources Division (GRD) Geologic Resources Inventory (GRI) Program. Index maps by James Winter. Bedrock sketch graphic clean-up by James Winter and Kari Lanphier. Quality control of this document by Stephanie O'Meara and Derek Witt (Colorado State University).

The information contained here was compiled to accompany the digital geologic-GIS maps and other digital data for Boston Harbor Islands National Recreation Area, Massachusetts (BOHA) developed by Georgia Hybels (NPS GRD), Stephanie O'Meara, Derek Witt and Jim Chappell (Colorado State University) using source data provided by Boston University and Massachusetts Geological Survey. Quality control provided by Stephanie O'Meara

GRI finalization by Stephanie O'Meara.

GRI program coordination and scoping provided by Bruce Heise and Tim Connors (NPS GRD, Lakewood, Colorado).