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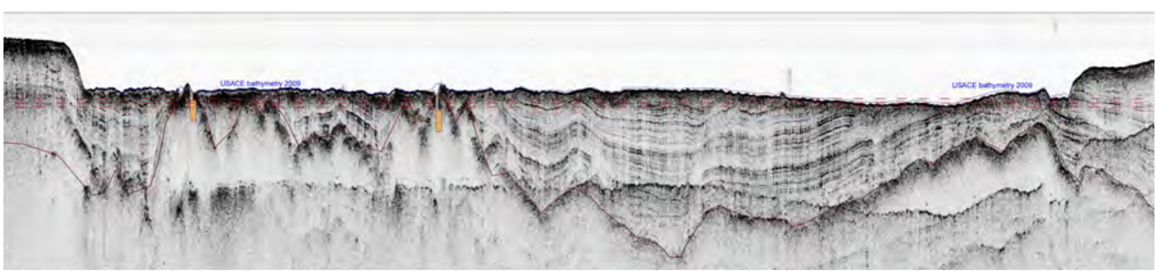

Report through Section 4

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e4sciences | Earthworks, LLC
27 Glen Road, North Entrance
Sandy Hook, Connecticut 06482
P.O. Box 178, Newtown, CT 06470
(203) 270-8100, Fax (203) 364-0480
www.e4sciences.com

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Executive summary

The United States Army Corps of Engineers, New England District (USACE-NAE), is deepening Boston Harbor to accommodate deeper-draft ships. The channel floor is composed of a variety of materials from fine-grained organic-rich sediments to Neoproterozoic rock. Removing these materials by dredging presents a challenge to (a) maximize efficiency and (b) reduce the environmental footprint.

The NAE assigned e4sciences (e4) to investigate the configuration and the materials in the dredging prism. This comprehensive report estimates the characteristics of the channels, and of the materials to be dredged. This report details independent data from 26 borings, sample analyses, sonar imaging, and reflection seismology. e4 processed each dataset separately. The processed results were then integrated to produce a comprehensive analysis of the materials in the dredging prism.

The strata of interest are the Holocene sediments, Pleistocene Boston Blue Clay, Pleistocene till, weathered Neoproterozoic Cambridge Argillite, and fast Neoproterozoic Cambridge Argillite. A Jurassic diabase was observed in boring FD14-26 outside of the required dredging volume.

The principle issues of concern are (a) rock properties, (b) sediment properties, (c) bathymetry, (d) infrastructure, and (e) debris.

The harbor deepening consists of three distinct project segment depths: the -51ft project segments, the -47ft project segments, and the -45ft project segment. Each project is divided into three distinct elevations: (1) the newly authorized required grade; (2) 2ft of optional paid overdepth in ordinary material, or required overdepth in the case of rock or hard bottom; (3) and an additional optional 2ft-paid overdepth in the case of rock or till at grade and the first overdepth.

The total volume to the newly authorized grade is 8.09 million cuyd including side slopes (Table ES-1). The volume of the rock is less than 1% of the total volume to be removed to the newly authorized grade. A small portion of the rock, mostly in the North Channel and Main Ship Channel in the Reserved Channel area, is fast rock. Fast rock is defined as rock whose compressional wave velocity is faster than 2,700m/s. The total amount of fast rock above grade is 2,944cuyd. That constitutes less than 0.04% of the total volume or less than 3% of the volume of rock. e4sciences calculated an error of ±3% on each of these volume estimates. No contingency was applied to any of these estimates. The USACE has tested the silt in President Roads Anchorage and the Reserved Channel areas as suitable for ocean disposal.

Table ES-1. Total volume estimates for the newly authorized grade in Boston Harbor deepening project. MSCPRA = Main Ship Channel in President Roads Anchorage area, PRA = President Roads Anchorage area, MSCRCA = Main Ship Channel in Reserved Channel area, RC = Reserved Channel, TB = Turning Basin, MSCMMT = Main Ship Channel at the Massport Maritime Terminal.

	Grade	Channel volume to grade	Volume of side slope to grade	Sum of volumes above grade	Fraction of total volume
Channel	ft, MLLW	cuyd	cuyd	cuyd	per interval
North Channel	-51	2,686,253	134,541	2,820,793	0.3521
MSCPRA -51ft	-51	47,672	3,173	50,845	0.0063
MSCPRA -47ft	-47	473,226	15,572	488,799	0.0610
PRA	-47	2,384,733	39,056	2,423,788	0.3025
MSCRCA	-47	1,321,583	123,763	1,445,346	0.1804
Reserved Channel	-47	356,346	22,928	379,274	0.0473
Turning Basin	-47	235,649	7,183	242,831	0.0303
MSCMMT	-45	150,740	9,523	160,263	0.0200
Total		7,656,200	355,739	8,011,939	1.0000

Adding an additional 2ft for paid overdepth and the required overdepth in the case of hard bottom or rock throughout the project adds 3.52 million cuyd and raises the total volume to 11.53 million cuyd (Table ES-2). The volume of rock rises to 0.28 million cuyd or 22% of the total cumulative volume. In the first overdepth, the volume of fast rock 8,219cuyd or 5% of the total rock.

Table ES-2. Total volume estimates to 2ft overdepth in ordinary material or required overdepth in the case of rock or hard bottom in Boston Harbor deepening project.

	Sum of all volumes above grade	First overdepth	Volume from grade to overdepth	Volume of side slope from grade to OD1	Interval volume	Sum of volumes above overdepth	Fraction of total volume
Channel	cuyd	ft, MLLW	cuyd	cuyd	cuyd	cuyd	per interval
North Channel	2,820,793	-53	865,127	27,122	892,249	3,713,042	0.3219
MSCPRA -51ft	50,845	-53	25,488	3,250	28,738	79,583	0.0069
MSCPRA -47ft	488,799	-49	419,522	17,292	436,814	925,613	0.0803
PRA	2,423,788	-49	1,100,851	33,685	1,134,536	3,558,324	0.3085
MSCRCA	1,445,346	-49	592,635	61,288	653,923	2,099,269	0.1820
Reserved Channel	379,274	-49	139,890	10,882	150,772	530,046	0.0460
Turning Basin	242,831	-49	86,905	6,553	93,458	336,289	0.0292
MSCMMT	160,263	-47	117,718	13,069	130,787	291,050	0.0252
Total	8,011,939		3,348,135	173,142	3,521,277	11,533,216	1.0000

In the case of rock or hard bottom, an optional 2ft overdepth beyond the required 2ft overdepth is allowed. This second overdepth adds 0.49 million cuyd and raises the total volume of material to be dredged to 12.02 million cuyd (Table ES-3). The second overdepth raises the total volume of rock to 495,659cuyd. This estimate puts the total volume of rock at roughly 4.1% of the total cumulative volume to the second overdepth. The cumulative total amount of fast rock is 46,092cuyd and constitutes less than 9.3% of total rock volume.

Table ES-3. Total volume estimates to the second 2ft optional overdepth in the case of rock or hard bottom in Boston Harbor deepening project.

	Sum of all volumes above first overdepth	Optional second overdepth in case of rock	Interval volume from first to second overdepth in case of rock or hard bottom	Sum of all volumes above second overdepth	Fraction of total volume
Channel	cuyd	ft, MLLW	cuyd	cuyd	per interval
North Channel	3,713,042	-55	274,012	3,987,054	0.3316
MSCPRA -51ft	79,583	-55	0	79,583	0.0066
MSCPRA -47ft	925,613	-51	163	925,775	0.0770
PRA	3,558,324	-51	9,409	3,567,733	0.2967
MSCRCA	2,099,269	-51	79,372	2,178,640	0.1812
Reserved Channel	530,046	-51	56,856	586,902	0.0488
Turning Basin	336,289	-51	14,078	350,368	0.0291
MSCMMT	291,050	-49	56,204	347,254	0.0289
Total	11,533,216		490,094	12,023,310	1.0000

In the North Channel, the volume of rock and till is 377,763cuyd above grade and that constitutes 3.6% of total volume. In the North Channel, volume of fast rock is 19,000cuyd, or less than 13% of the total rock volume. In the Main Ship Channel in Reserved Channel area, the rock and till constitutes 145,057cuyd, and that is less than 7% of the total volume. In the Reserved Channel, the rock represents as much as 20% of the total volume. In the Reserved Channel, 17% of the rock is fast rock. In the Main Ship Channel at the Massport Maritime Terminal, fast rock is a small concern. In the Main Ship Channel in the President Roads area, the rock is an even smaller concern.

Table ES-4 summarizes the total volume of material required to be dredged. The sum consists of the material above newly authorized grade and the material above the required overdepth in case of rock or hard bottom. The total required volume to be dredged is 8.09 million cuyd.

Table ES-4. Estimates of required volumes to grade and required overdepth. The fractions are per reach.

	Grade	Total volume to grade including side slopes	Volume of till/rock from grade to OD 1	Volume of sediment in areas of till/rock from grade to first overdepth	Total
Reach	ft, MLLW	cuyd	cuyd	cuyd	cuyd
North Channel	-51	2,686,253	250,677	11,395	2,948,325
MSCPRA -51ft	-51	47,672	0	0	47,672
MSCPRA -47ft	-47	473,226	8	20	473,255
PRA	-47	2,384,733	2,666	1,909	2,389,307
MSCRCA	-47	1,321,583	57,500	7,842	1,386,925
Reserved Channel	-47	356,346	39,146	5,917	401,408
Turning Basin	-47	235,649	7,840	1,870	245,359
MSCMMT	-45	150,740	39,228	8,803	198,771
Total		7,656,200	397,065	37,757	8,091,022

Live infrastructure such as cables and pipelines may need to be moved before it delays the project. The crossings in the Main Ship Channel in Reserved Channel area may need to be removed or abandoned. We have not been assigned a one-to-one identification of the pipes and cables in the channels. The proximal utilities should be mapped and resolved as soon as possible.

If pipelines crossing the channel are abandoned, or cleaned and capped, then the materials become debris. If abandoned, beware of possible leaks or spills during removal. The cables and pipelines in the Main Ship Channel in President Roads Anchorage area are deep enough not to be of concern except on the slope. However, all infrastructure regardless of depth should be marked on the plans to warn about no spudding.

The various areas that e4 investigated have enough differences among them that they may warrant discrete consideration for separate dredging contracts. Separate smaller contracts may also provide the opportunity to apply lessons learned.

Heave and ocean swells may likely be a factor in lost time during the deepening project.

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Plate 34. Main Ship Channel at Massport Maritime Terminal seismic-velocity cross sections

1.0 Introduction

The United States Army Corps of Engineers, New England District (USACE-NAE), is deepening Boston Harbor to accommodate deeper-draft ships. The channel floor is composed of a variety of materials from fine-grained organic-rich sediments to Neoproterozoic rock. Removing these materials by dredging presents a challenge to (a) maximize efficiency and (b) reduce the environmental footprint.

The NAE assigned e4sciences (e4) to investigate the configuration and the materials in the dredging prism. This comprehensive report estimates the characteristics of the channels, and of the material to be dredged. This comprehensive report details independent data from 26 borings, sample analyses, sonar imaging, and reflection seismology. e4 processed each dataset separately. The processed results were then integrated to produce a comprehensive analysis of the materials in the dredging prism.

Figure 1 is a location map showing the reaches and the turn points. Table 1 lists the project chronology.

Table 1. Project chronology.

		Description	Start	Finish
			(yyyy.mm.dd)	(yyyy.mm.dd)
1		Notice to proceed	2014.09.03	2014.09.03
2	Task 1	Review of existing data, tidal plan	2014.06.27	2015.04.28
3	Task 1	WP, AHA, TCP, APP	2014.10.01	2014.10.31
4	Task 5	One call for borings	2014.11.17	2014.11.17
5	Task 2	Mobilization of *Time and Tide*	2014.10.29	2014.11.06
6	Task 3A	Side-scan acquisition	2014.11.11	2014.12.22
7	Task 3	Sub-bottom acquisition	2014.11.11	2014.12.22
8	Task 3	Waveform migration	2014.12.22	2015.04.30
9	Task 4	Interim progress report	2015.01.15	2015.04.31
10	Task 4	Progress report	2015.01.30	2015.01.30
11	Task 5	Magnetometer acquisition	2014.12.23	2014.12.23
12	Task 5	Mobilization of jack-up	2014.11.13	2014.11.17
13	Task 5	Jack-up on site	2014.11.17	2014.11.17
14	Task 6	Water borings acquired	2014.11.24	2014.12.20
15	Task 1	Bathymetry from USACE	2014.11.23	2015.04.23
16	Task 2	Orthosonograph™ processing	2014.11.13	2015.01.05
17	Task 3	Sub-bottom processing	2014.11.22	2015.04.27
18	Task 5	Magnetometer processing	2015.01.07	2015.01.07
19	Task 5	Utilities	2014.11.15	2014.12.31
20	Task 6	Borings	2014.11.30	2014.12.24
21	Task 7	Rock mechanics testing	2015.01.15	2015.04.15
22	Task 7	Geotechnical analysis results	2015.04.15	2015.04.15
23	Task 8	Top-of-rock map	2015.04.15	2015.04.31
24	Task 8	Integration of bathymetry	2015.04.15	2015.04.31
25	Task 8	Geological maps	2015.01.31	2015.04.31
26	Task 8	Geotechnical maps	2015.01.31	2015.04.31
27	Task 8	Volume estimations	2015.04.01	2015.05.08
28	Task 8	Draft report	2015.03.18	2015.05.08
29	Task 8	Final report	2015.04.16	2015.05.15

1.1 Channels and grade

The harbor deepening consists of three distinct projects: the -51ft project, the -47ft project, and the -45ft project. Each project is divided into three distinct dredge elevations: the authorized grade; the first paid overdepth or in the case of rock the required overdepth; and in the case of rock in the first overdepth, the second paid overdepth.

Figure 1 is a location map showing the various areas and channels within the deepening project. Figure 2 plots the multibeam bathymetry for the area-of-investigation in Boston Harbor. The USACE-NAE acquired the multibeam over several periods. They measure the first dataset between 2005 and 2011, mostly in 2009. They acquired the second set in 2012. The third dataset was measured in 2014. The map in Figure 2 is a composite of the most recent elevation available at any given point.

Table 2 lists the channels, existing grade, the newly authorized and required grade, optional paid overdepth for ordinary sediments or required overdepth in case of rock or hard sediments, and an optional paid overdepth in case of rock or hard sediments. The paid overdepth in case of rock or till adds another two feet to the required overdepth if rock or hard till is observed in the required grade and required overdepth prisms. Figure 3 sketches the plans for the dredging grade: the newly authorized grade, paid overdepth or required overdepth in the case of rock, and additional paid overdepth in case of rock or till.

Table 2. Channel characteristics. MSCPRA = Main Ship Channel in President Roads Anchorage area. MSCRCA= Main Ship Channel in the Reserved Channel area. MSCWMMT= Main Ship Channel at the Massport Maritime Terminal.

Reach	Current grade	Newly authorized grade	Optional overdepth or required overdepth in the case of rock	Optional paid overdepth in case of rock
	MLLW, ft	MLLW, ft	MLLW, ft	MLLW, ft
North Channel	-40	-51	-53	-55
MSCPRA -51ft	-40	-51	-53	-55
MSCPRA -47ft	-40	-47	-49	-51
President Roads Anchorage	-40	-47	-49	-51
MSCRCA – South lane	-40	-47	-49	-51
Reserved Channel	-40	-47	-49	-51
MSCMMT – South lane	-40	-45	-47	-49

The deepening project was divided into three areas: the North Channel area, the President Roads area, and the Reserved Channel area. The various channels of differing grades do not necessarily conform to these boundaries. Table 3 lists the reaches in the Boston Harbor Deepening Project.

Table 3. Reaches considered in the Boston Harbor Deepening project.

Reach	Project elevation	Deepening areas	Portion not at existing grade
North Channel	-51ft-2ft	Main Ship Channel	Triangle at turn
		Slopes	
President Roads area	-51ft-2ft	Main Ship Channel	
		Slopes	
	-47ft-2ft	Main Ship Channel	
		Slopes	
	-47ft-2ft	Anchorage	
		Slopes	
Reserved Channel area	-47ft-2ft	Main Ship Channel	
		Slopes	
	-47ft-2ft	Reserved Channel	Drydock approach
		Slopes	
	-47ft-2ft	Turning Basin	Northeast corner
		Slopes	
	-45ft-2ft	Main Ship Channel	
		Slopes	

The properties of the rock vary greatly as a function of location throughout the harbor. The areas that have ordinary sedimentary material allow for an optional 2ft paid overdepth beyond the required grade. The areas that have a hard bottom (rock or hard till) require the 2ft overdepth be achieved. The areas of hard bottom allow for an additional optional 2ft deeper overdepth. Review the sketches in Figure 3. Table 4 sketches the elevations for each of the depths in the reaches.

Table 4. Reaches and their characteristics in the Boston Harbor deepening project.

Elevation	-51ft project		-47ft project		-45ft project	
ft, MLLW	Areas of ordinary material[1]	Areas of hard bottom material[2]	Areas of ordinary material[1]	Areas of hard bottom material[2]	Areas of ordinary material[1]	Areas of hard bottom material[2]
-45					Authorized grade	Authorized grade
-47			Authorized grade	Authorized grade	Optional overdepth	Required overdepth
-49			Optional overdepth	Required overdepth		Optional overdepth
-51	Authorized grade	Authorized grade		Optional overdepth		
-53	Optional overdepth	Required overdepth				
-55		Optional overdepth				

1. Areas of sediment other than cobble and glacial till
2. Areas of rock or other hard bottom materials like cobble and glacial till

1.2 Stratigraphy

The strata of interest are the Holocene sediments, Pleistocene Boston Blue Clay, Pleistocene till, Jurassic diabase, weathered Neoproterozoic Cambridge Argillite, and fast Neoproterozoic Cambridge Argillite.

e4 observed several different geological units in the harbor. Table 5 lists the geological units from youngest at the top to the oldest at the bottom. The basement rock is the Cambridge Argillite. Minor intrusions both of both Paleozoic and Jurassic felsic and mafic intrusive are possible. Contact metamorphism has been associated with these intrusions.

Table 5. Strata of Boston Harbor.

	Geological unit	Age	Description	Geotechnical
1	Silt	Holocene - industrial	Fine-grained organic-rich silt	Silt
2	Sands	Holocene	Medium grained with whole shells, shell material, sand waves	Holocene sediment
3	Gravel	Holocene	Sand plus fine gravel, pebbles and cobbles, reworked till	Holocene sediment
4	Clay and silt	Holocene	Estuarine fine-grained deposits	Holocene sediment
5	Peat	Holocene	Soils	Holocene sediment
6	Boston Blue Clay	Pleistocene	Find-grained ,highly layered, glacial marine clay	Pleistocene sediment
7	Pleistocene till #2	Pleistocene	Boulders, gravels, sand	Till
8	Pleistocene till #1	Pleistocene	Sandy	Till
9	Jurassic diabase	Jurassic	Fine-grained diabase, intrusive igneous rock	Rock
10	Cambridge Argillite	Neoproterozoic	Slightly metamorphosed, weathered, layered, sedimentary rock	Rock
11	Cambridge Argillite	Neoproterozoic	Slightly metamorphosed, fast, layered, sedimentary rock	Rock

Fast rock is defined as rock whose seismic compressional wave velocity is greater than 2,700m/s (8,855ft/s). Section 1.5 explains the reasoning for the fast rock delineation.

Figure 3 displays the stratigraphic schematic for the North Channel (above) and the Main Ship Channel (below) to the Reserved Channel, respectively. The Holocene sediment lies on top of the Pleistocene sediments. The Pleistocene sediments lie on Pleistocene till. The Quaternary sediments lie on top of the Cambridge Argillite.

1.3 The objective of the comprehensive report

The objective of this comprehensive report on explorations is to produce estimates of the dredging expectations of the rock, sediments, debris, and infrastructure in the area of investigation. The estimates include maps, volumes, and theory to the materials encountered in the dredging prism within the channels. We do not own dredging equipment, and the performance of each tool in dredging is machine specific. Therefore, we use seismic compressional wave velocity to define the differences in rock resistance to digging.

The strata of interest are the Holocene sediments, Pleistocene Boston Blue Clay, Pleistocene till, weathered Neoproterozoic Cambridge Argillite, and fast Neoproterozoic Cambridge Argillite.

The harbor deepening consists of three distinct project segments: the -51ft project, the -47ft project, and the -45ft project.

Each project is divided into three distinct elevations: (1) the newly authorized required grade; (2) the first paid overdepth or in the case of rock the required overdepth; (3) and in the case of rock in the first overdepth, the second paid overdepth.

1.4 Background on rock properties

The Cambridge Argillite underlies the Boston Harbor Channels. This Neoproterozoic rock formation is composed of highly variable, slightly metamorphosed, weak, layered, sedimentary rock. The beds strike variably from the east to west and to the north. The cleavage dips to the north and west. The argillite varies from decomposed to massive. Most of the argillite in the dredging prism is decomposed and highly weathered (Table 6). Some of the argillite is massive and is fast rock.

Table 6. Rock types.

Formation	Type	Configuration	RQD	Location
Cambridge Argillite	Decomposed	Ridges	NA	All
	Decomposed	Pinnacles	NA	All
	Highly weathered	Ridges	10>RQD	All
		Pinnacles	10>RQD	All
	No observed cleavage	Ridges	50>RQD>10	PRA
		Pinnacles	50>RQD>10	PRA
	Broken with cleavage	Ridges	75>RQD>50	PRA, MSCRCA, Reserved Channel, TB, MSCMMT
		Pinnacles	75>RQD>50	PRA, MSCRCA, Reserved Channel, TB, MSCMMT
		Knobs	RQD>50	PRA, MSCRCA, Reserved Channel, TB, MSCMMT
	Massive with cleavage	Knobs	RQD>50	MSCRCA

Rock Quality Designation (RQD) provides a semi-quantitative measure of the jointing, fractures, and bed separations in cores. RQD relates well to fracture density and rippability.

Productivity measures the results of the dredging process. Productivity is a flux, volume per unit time, measured in cubic yards per hour. Productivity in dredging is equal to (a) the volume of material removed from the source (channel bottom) per unit time (hours), or (b) the volume of material placed into the scow per unit time, or (c) the volume of material deposited at the placement site per unit time. In this project, we used the volume of in-situ material in cubic yards removed from the channel bottom per hour.

Rippability is an effective engineering property of a material. It is not an intrinsic property; it is not observer invariant; it depends on the equipment being used. In this report, rippability in dredging is a measure of the material response of the channel bottom to penetration by a specific excavator with a specific bucket with a specific number of teeth in a specific manner. Ripping by an excavator is a form of treatment that breaks up the rock so that the rock can be removed. Ripping costs must be compared to the costs of other methods of loosening material on a cubic yard basis. It is generally thought to be safer than blasting. Tooth penetration is often the key to ripping success. The penetration force is the maximum sustained downward force generated by hydraulics at the ripper tip required to lift the dredge stern to a prescribed elevation. The breakout force is measured with the teeth impacting the top of the rock strata.

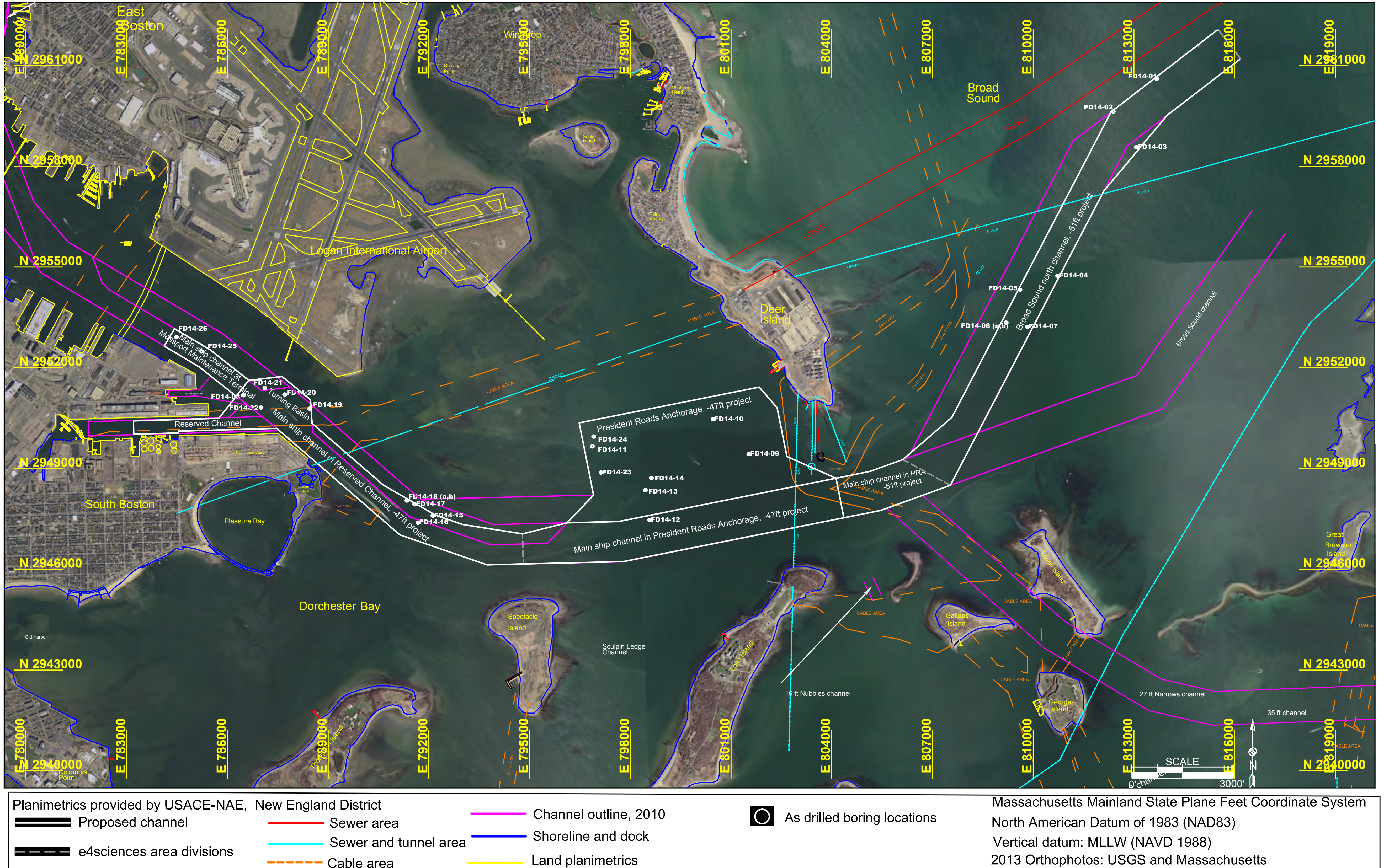

Figure 1. Location map of Boston Harbor deepening. The e4 core boring locations are plotted.

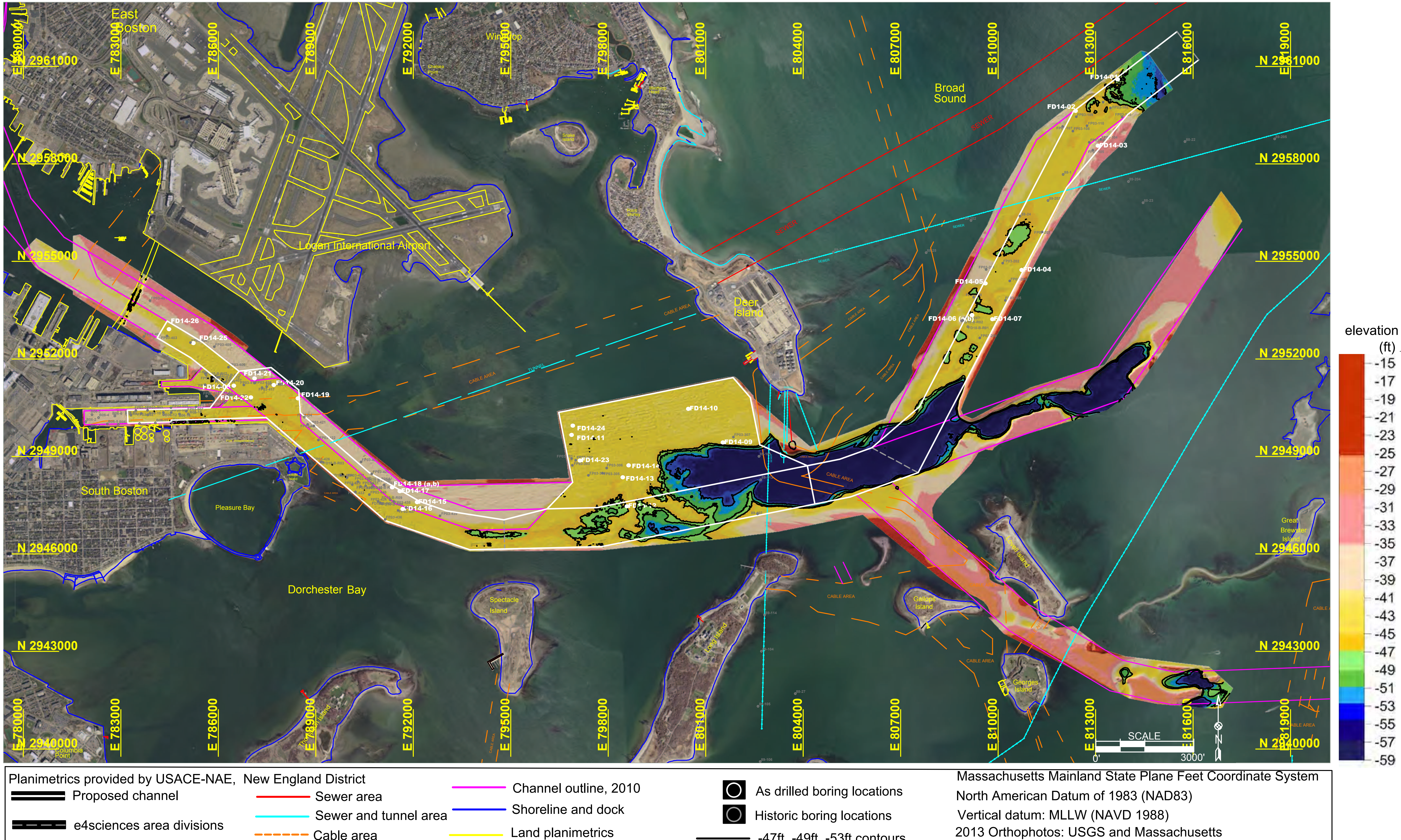

Figure 2. Multibeam bathymetry of Boston Harbor.

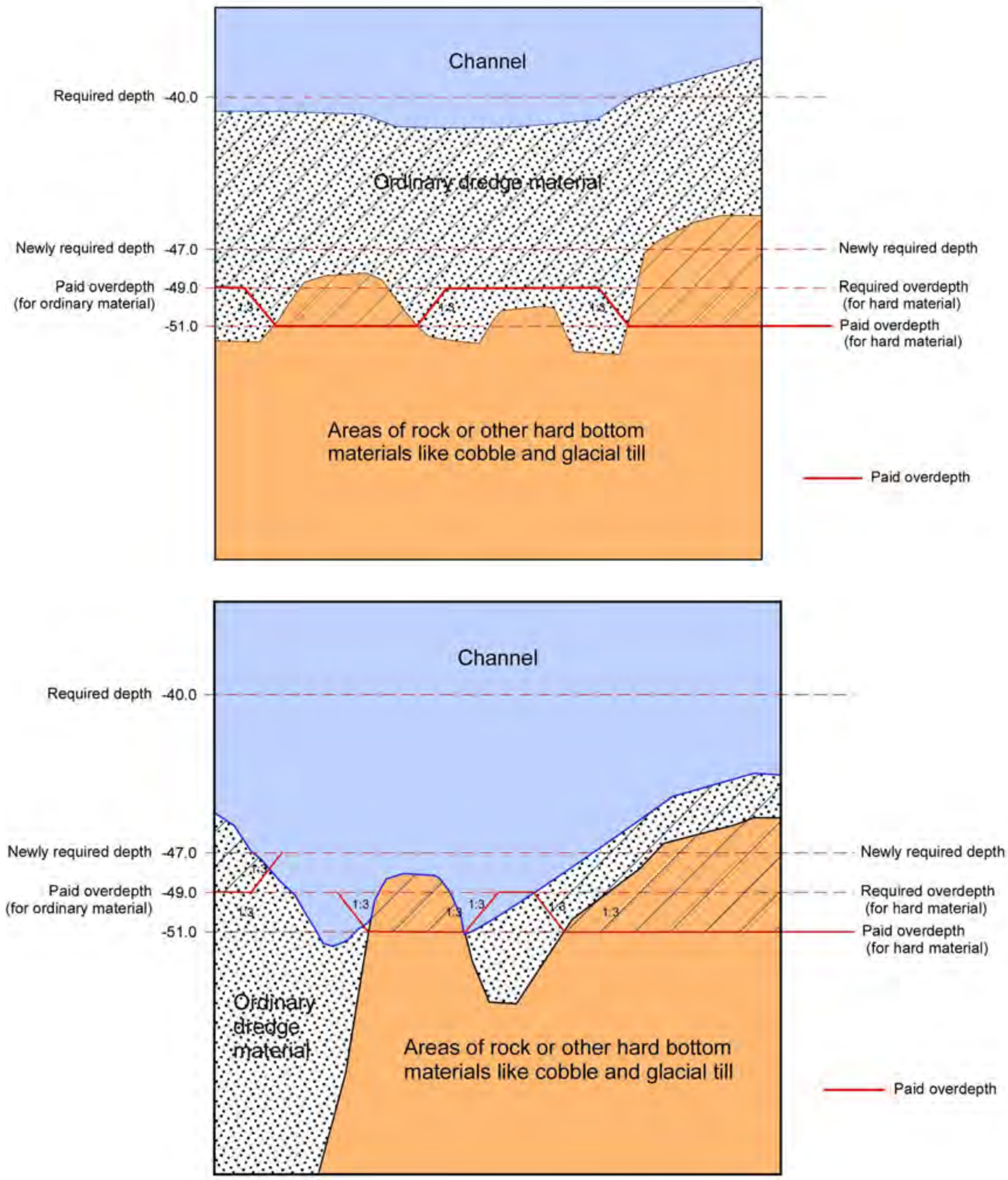

Figure 3. Sketches of the criteria for dredging grade and dredging overdepth. North Channel (above) and Main Ship Channel (below).

A clamshell dredge cannot rip, but it can penetrate softer rock. With a rock bucket a clamshell dredge can remove fragmented rock. An excavator can rip and perform production dredging. A cutter suction dredge performs ripping and fragmentation with a rotating head. Ripping is an art rather than a science and depends on operator skill and experience.[4] The operator must adjust the number of teeth used, the length and penetration of the teeth, direction, and throttle according to the conditions.

The Caterpillar Tractor Company defines rippability qualitatively as rippable, marginal, and/or non-rippable. Others define a semi-quantitative rating from 0-100; 0 being highly rippable and 100 being unrippable. In either definition, rippability is dimensionless.

Caterpillar Tractor Company has long related seismic velocity to production and rippability.[1,2] Caterpillar relates rippability and production in the following way: the productivity is measured by recording the time spent ripping, then by removing and weighing the ripped material. The total weight divided by the time spent is equal to the hourly production. If measured by volume in a scow, then the density is used to calculate the volume and so the estimate is only as good as the density measured.

Several articles in the geotechnical literature address relationships between rock properties and productivity.[3,4,5] Rock mass characteristics further complicate the estimates of rippability and production in Boston Harbor. The Cambridge Argillite underlying Boston Harbor has a high degree of stratification, planes of weakness, weathering, and fracturing.

1.5 Seismic velocity and rippability

The seismic results are evaluated in terms of seismic (compressional wave velocity), V_p, where

$$\rho V_p^2 = M_o(1-\phi)^m \qquad (1)$$

ρ is the density of the rock, M_o is the modulus of solid grains in GPa, ϕ is the porosity, and the exponent, m, is roughly 6 for fractures. A compressional-wave velocity of 2,000m/s may distinguish unconsolidated sediments from consolidated rock. A compressional-wave velocity of 2,700m/s (8,856ft/s) may estimate less rippable rock. The unconfined compressive strength, C_s, varies similarly with porosity.

$$C_s = C_o(1-\phi)^n \qquad (2)$$

Figure 4 graphs the D-11R ripping performance of various rocks versus seismic velocity on land.

Figure 5 plots the data that Caterpillar measured for D-10 productivity versus seismic velocity. The productivity vanishes above 3,000m/s (9,840ft/s).

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[1] Caterpillar Performance Handbook, Edition 36, Caterpillar, Peoria, IL, 2006.
[2] Caterpillar, Handbook of Ripping, 8th Edition, Caterpillar, Peoria, IL, 2000.
[3] Department of the Army, US Army Corps of Engineers, Rock mass classification data requirements for rippability, Technical Letter No. 1110-2-28, 1983.
[4] McCann, D., and P. Fenning, Estimation of rippability and excavation conditions from seismic velocity measurements, in Engineering Geology of Construction, Eddleston, M., et al., (eds.) Geological Society of reengineering Geology Special Publication, 335-343, 1995
[5] MacGregor, F., R.Fell, G. Mostyn, G. Hocking, and G. McNally, The estimation of rock rippability, Quarterly Journal of Engineering Geology 27, 123-144, 1994.

Figure 6 plots the Caterpillar data for D-10 productivity in softer rocks. Note the large variation particularly in sandstones due to favorable or adverse conditions. These conditions relate to moisture, weathering, jointing, strata, and fracturing.

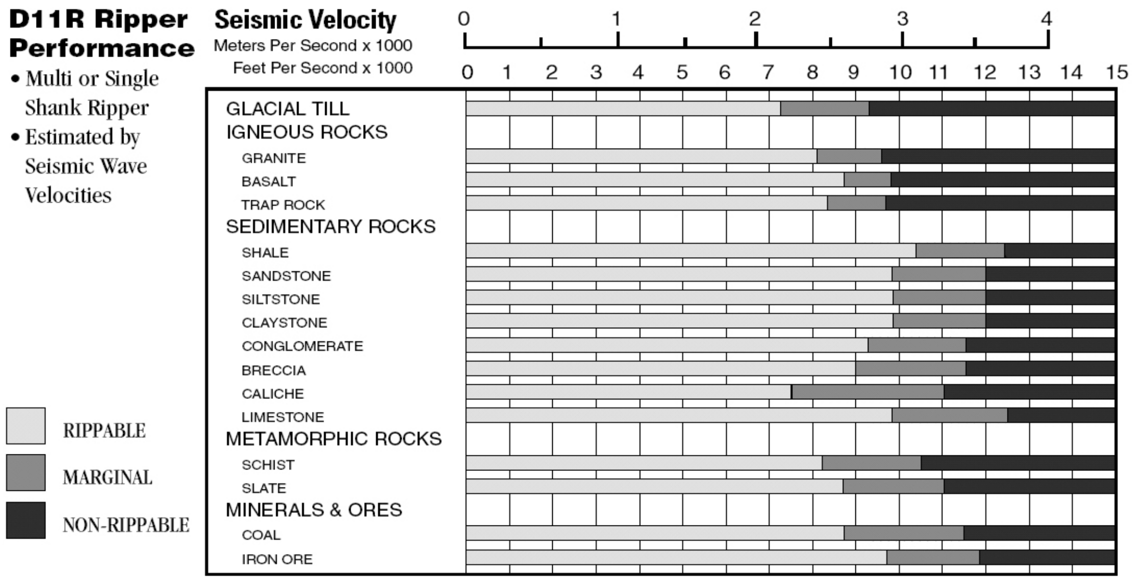

Figure 4. D-11R ripper performance on land in a variety of rocks and sediment (from Caterpillar, 2006).

Rock Quality Designation (RQD) provides a semi-quantitative measure of the jointing, fractures, and bed separations in cores. RQD relates well to fracture density and rippability.[5,6] A low RQD (<50) may be removed with an excavator or a large clamshell. The RQDs for each boring are listed in the boring description. We use the RQD to classify the rock locally as the dredgers would do the same.

[6] ASTM D6032-08, Standard Test Method for determining Rock Quality Designation of Rock Core.

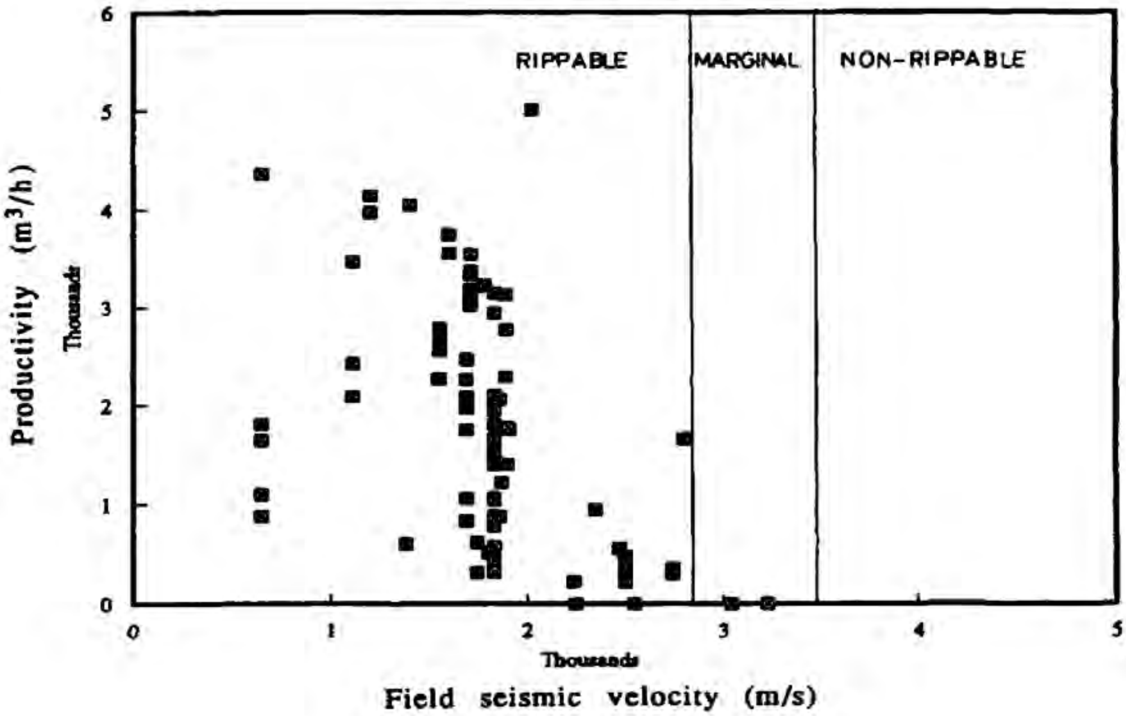

Figure 5. Productivity in m^3/hour of a D-10 tractor in sandstones (from MacGregor et al., 1994).

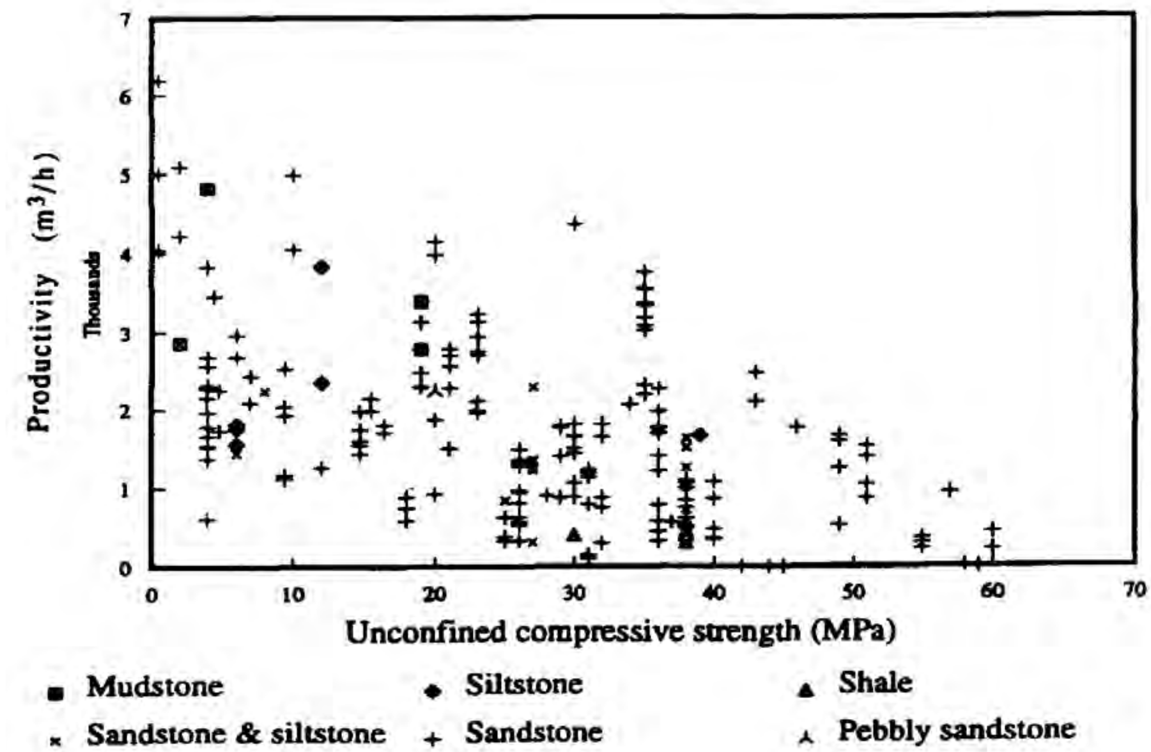

Figure 6. D-10 tractor productivity versus unconfined compressive strength in sedimentary rocks over a range of compressive strengths (70MPa=10.15kPSI) not unlike the S-AK-2/3. (From MacGregor et al., 1994).

2.0 Scope of work

The e4 team has conducted the tasks and options presented in the NAE's Scope of Work, dated 06 August 2014. The tasks are:

Task 1 – Work Plan, Tidal Correction Plan (TCP), Accident Prevention Plan (APP), & Activity Hazard Analysis (AHA)
Task 2 – Seismic survey mobilization/demobilization
Task 3 – Seismic reflection survey
Task 4 – Report of seismic reflection survey
Task 5 – Drilling mobilization/demobilization
Task 6 – Boston Harbor borings

Option 3A – Side-scan sonar survey
Option 6A – Additional borings
Option 6B – Additional single boring
Option 7 – Rock mechanics testing and report
Option 8 – Boston Harbor report of explorations
Option 9 – Weather delay (Multi-executable)

Options 3A, 7, 8, and 9 were awarded at the time of Notice to Proceed.

The location of the borings depended on the results of the seismic survey. The drilling operations commenced as soon as feasible after the commencement of the seismic reflection survey. The order of borings depended on sea conditions and vessel traffic. In the following section these tasks are discussed together.

2.1 Task 1 – Work Plan, Tidal Correction Plan, Accident Prevention Plan and Activity Hazard Analysis

a. Work Plan. The Work Plan addressed the seismic reflection survey and the marine boring program as well as described all procedures, personnel, subcontractors, proposed methods, proposed equipment, proposed field boring log form, and final boring log format, and general sequence of work. The marine plant was sufficiently sized and equipped to provide a safe and stable work platform considering the water depths and tidal range at the site. The work plan included a description of the proposed marine plant and personnel qualifications.

Water depth in the area of the borings is typically a minimum of approximately 40 feet, and the area is subject to a mean tidal range of about 9.5 feet. e4 was responsible for identifying the range of depths throughout the project and provided the necessary equipment (e.g. jack-up barge) to accommodate this range of conditions.

e4 obtained all necessary clearances and state and local permits. Permits for drilling work in Boston Harbor have not been required in the past. e4 was responsible for coordinating all aspects of the work, making necessary port and docking arrangements, and coordinating in advance with the Coast Guard and Harbor Master.

The seismic reflection survey and borings are located within a Federal government maintained navigation channel and rights-of-entry were not required. Boston Harbor channels are mainly used by deep draft commercial vessels, fishing vessels, and numerous small recreation and commercial crafts, which may cause some interference with contract operations. Certain restrictions on vessel movement are in place when liquid natural gas (LNG) tankers traverse the harbor. e4 was required to conduct the work in such a manner as to obstruct navigation as little as possible, and in the event e4's plant so obstructed the channel as to make difficult or endanger the passage of any vessels, the plant promptly moved on the approach of any vessel to such an extent as was necessary to afford a practicable passage. Moving of e4's plant may also have been based on the determination of the docking pilot if vessel traffic required it. e4 was required to perform the work from a marine/floating plant and make all required notifications. e4 made their own investigations of limitations of access and docking or launching facilities to be used by e4 to complete the work. e4 also contacted NSTAR, NATIONAL GRID, VERIZON, MWRA, and Municipal Sewer and Water Departments to determine location of utilities under that portion of the Main Shipping Channel. See Attachment A for a description of anecdotal reports of known and suspected utilities within the Boston Harbor navigation channels.

e4 described the methods for accurately finding and determining drilling locations horizontally with sub-meter accuracy, and for achieving vertical accuracy in the measurement of exploration depths. Drilling depths were accurate to +/- 6 inches.

b. Tidal Correction Plan. e4 developed a written plan describing the procedures to be used to determine boring depths and tidal corrections and submitted this plan to NAE for approval prior to field work. e4 explained how tidal corrections were made. Differential GPS methods and tide boards were required for this project. NAE already had some tide boards established in the area that e4 used for this purpose. For the borings in the Broad Sound North Entrance Channel, tide readings at Boston Light were used to determine water elevations at the time of drilling.

c. Accident Prevention Plan (APP). e4 prepared an Accident Prevention Plan (APP) specific to the activities being performed. It included an Activity Hazard Analysis as described below. All fieldwork, including mobilization and demobilization, was conducted in accordance with the final approved APP and AHA, the U.S. Army Corps of Engineers Safety and Health Requirements Manual (EM 385-1-1, 2008), and all applicable federal, state, and local safety and health requirements. The APP was approved prior to any fieldwork being performed.

The APP detailed how safety and health was managed during the project. The APP addressed the requirements of applicable Federal, State and local safety and health laws, rules, and regulations. e4 complied with Federal Acquisition Regulation Clause No. 52.236-13 for Accident Prevention, which is added by reference. Special attention focused on the requirements of the US Army Corps of Engineers Safety and Health Requirements Manual, EM 385-1-1 (2008) specifically Appendix A in EM 385-1-1, (Minimum Basic Outline for Accident Prevention Plan), and Section 01.A.11 through 01.A.13, and Figure 1-1 (Activity Hazard Analysis (AHA)). Work did not proceed until the APP had been reviewed by the Corps Safety Manager and was accepted by the Contracting Officer Representative.

The APP interfaced with e4's overall safety and health program. Any portions of e4's overall safety and health program referenced in the APP was included in the applicable APP element and made site-specific. The Government considers e4 to be the "controlling authority" for all work site safety and health of the subcontractors. e4 was responsible for informing their subcontractors of the safety provisions under the terms of the contract and the penalties for noncompliance, coordinating the work to prevent one craft from interfering with or creating hazardous working conditions for other crafts, and inspecting subcontractor operations to ensure that accident prevention responsibilities are being carried out. The APP was signed by the scientist preparing the APP, the on-site superintendent, the designated site safety and health officer, and any designated CSP and/or CIH.

All personnel, especially those operating the marine plant, are experienced and possess all licenses and permits needed. The Plan included a description of the marine plant and crew, and provided documentation that the plant and crew met all safety requirements, including any inspections or certification of the vessels required by the Coast Guard. Even if a vessel is exempt from Coast Guard inspection, NAE requires a current vessel inspection report be provided in the Accident Prevention Plan.

Also, any manufacturer's information regarding stability and operating restrictions for the floating plant was included in the APP. e4 insured that the requirements of EM 385-1-1, Section 19 were followed in regards to marine vessel operations and safety.

The marine plant was operated by personnel with sufficient marine experience. Submittal included a resume of the vessel operator's experience for approval by USACE. Even if a captain's license is not required to operate the vessel or marine plant, e4 must still comply with the boat operators training requirements of the regulations and at a minimum meet the requirements of EM 385-1-1 and applicable State Standards. The lead vessel operator was placed in charge of ensuring all marine safety precautions were followed. The operator was required to monitor and log all weather conditions obtained through radio broadcasts throughout the day. e4 provided a Site Safety and Health Officer (SSHO) to insure that the APP is followed. The APP submittal included the qualifications of the SSHO for USACE approval. The SSHO qualifications included the following: Demonstrated work on similar projects; 10-hour OSHA construction safety class or equivalent within last 3 years; and documented experience conducting drilling and rock coring on marine plant. e4's geologist inspector may serve as the SSHO, however, the SSHO designated by e4 must be present at the work site at all times.

The APP detailed safe access and egress methods for any type of marine plant used in the work. Safe access and egress was maintained for all tide elevations. A Severe Weather Plan was submitted, and included means and methods of protecting personnel and equipment when severe weather was forecasted.

In addition, e4 conducted a safety meeting at the project site on the first day of work. Thereafter, safety briefings were held weekly; records of the safety briefings were submitted weekly. The inspector documented all safety meetings on a copy of the safety meeting form, attached.

d. Activity Hazard Analysis (AHA). An Activity Hazard Analysis was submitted for each major phase of work. A major phase of work is defined as an operation involving a type of work presenting hazards not experienced in previous operations or where a new subcontractor or work crew is to perform. The analysis defined all activities to be performed and identified the sequence of work, the specific hazards anticipated, and the control measures implemented to eliminate or reduce each hazard to an acceptable level.

Work did not proceed on that phase until the activity hazard analysis had been accepted by the Contracting Officer and a preparatory meeting had been conducted by e4 to discuss its contents with all engaged in the activities, including e4, subcontractor(s), and Government on-site representatives. The Activity Hazard Analysis was continuously reviewed and when appropriate modified to address changing site conditions or operations.

e. Accident Reporting: All accidents and near misses were to be investigated by e4. No work related recordable injuries, illness, and property damage accidents occurred. There was no need to report to the Contracting Officer's Representative within 48 hours of the incident and ENG Form 3394 occurred. Nor did the need arise to submit to the NAE Safety Manager any report within six working days of the incident.

2.2 Task 2 – Mobilization/Demobilization

e4 mobilized to the site the appropriate seismic reflection equipment necessary to perform sub-bottom profiling of the areas. e4 selected the most appropriate equipment to provide the appropriate balance between depth penetration and resolution for the conditions within each portion of the study area. Lower frequency equipment has greater depth penetration, but lower resolution while higher frequency equipment gives higher resolution, but does not penetrate as deep. Both lower frequency and higher frequency equipment were required to meet the quality objectives. The maximum dredge depth considered was -51 MLLW (-55 MLLW including 2 feet required overdredge and 2 feet allowable overdredge), and the exploration program was geared to acquire high-quality data to –60 MLLW. If acoustically opaque gas (entrapped in mud) was encountered, e4 did not need to propose any extraordinary measures to penetrate the mud acoustically. The areas showing difficult acoustically penetration were identified and noted.

e4 planned, coordinated, prepared, procured, supplied, and mobilized to the project site the necessary resources to meet the contract requirements, including all marine drilling plant and support vessels, pilots, operators and crew, drill rig, drill crew, geologist, supplies, and equipment capable of performing the work scoped in the exposed marine conditions of the outer navigation channels.

e4 was responsible for making all Notices to Mariners and coordinating with the Coast Guard and Harbor Master.

Before beginning operations, e4 coordinated with the U.S. Coast Guard to issue a "Notice to Mariners" regarding e4's operations. The U.S. Coast Guard point-of-contact for this project is as follows:

Commander Jason Smith, Chief, Prevention Department
Officer-in-Charge, Marine Inspection
U.S. Coast Guard Sector Boston
427 Commercial Street, Boston, MA 02109
Telephone 617-223-3032.
Email: jason.e.smith2@uscg.mil

The Harbor Master is:

Sgt. Joe Cheevers Boston Harbor Patrol Unit
34 Drydock Avenue
South Boston, MA 02127
617-343-4721

2.3 Task 3 – Seismic reflection survey

a. General. e4 provided all necessary labor, materials, and equipment necessary to complete the specified marine geophysics survey. e4 provided well-maintained and calibrated equipment, and a qualified crew experienced in all phases of marine geophysical explorations.

b. Qualifications. The lead geophysicist has at least five years experience conducting and interpreting results of marine geophysical explorations. Resume(s) of the lead geophysicist(s) was submitted with the e4's proposal.

c. Coordination. Details presented in this document were subject to change by NAE as the work progressed. Close coordination with the NAE point-of-contact listed was required during the operations to determine final details.

d. Utilities. Prior to starting any field work, e4 contacted the necessary agencies (e.g. DIG-SAFE for land operations) and/or utility companies to identify any utilities or other features in the areas to be explored, so they can be avoided and protected from damage by any invasive activities that may be taken during the explorations (e.g. setting anchors).

e. Base Maps. The Corps provided (1) electronic files of the most recent condition survey plans for the areas being studied in/along the Boston Harbor Navigation Channel on the USACE web page, (2) HYPACK electronic files containing the bathymetric data for the proposed dredge study areas, and (3) existing information regarding areas of known bedrock, encountered during previous maintenance dredging.

f. Density of Coverage. The distance between geophysical lines were selected to obtain adequate subsurface resolution needed to create bedrock contour maps with one-foot contour intervals. The number of lines was sufficient to acquire 100% coverage of proposed dredge areas, including some overlap along the edges. It was anticipated that geophysical lines would run roughly parallel to the channel, with cross lines (perpendicular) to the channel length, as needed to aid in interpretation of the data. Lines provided adequate coverage, extending slightly beyond the channel limits, to ensure that significant masses of bedrock, cobbles, etc. were not missed along the edges of the channel. e4 determined geophysical track line array, since selection may have been influenced by weather, logistics, geology, field findings, etc. Lines were numbered and identified in a fashion that allowed ease of use, and will avoid mistaking lines made in different areas. e4 determined nomenclature for identifying lines. During the geophysics phase, e4 collected surface grab samples as necessary for the purpose of ground-truthing the geophysical data and to aid in interpretation.

g. Vessel, Navigation, and Positioning. Vessel was sufficiently sized and equipped to conduct the required explorations, providing for protection of instrumentation and electronics, and able to accommodate the crew, captain, as well as visitors (1 to 2 Corps personnel). The vessel was captained by a U.S. Coast Guard licensed captain. e4 was responsible for making all Notices to Mariners, and all coordination with the Harbor Master, and other vessels operating in the area as identified earlier in this scope. The vessel was equipped with a Differential Global Positioning System (DGPS) with navigation software (HYPACK or equivalent) to enable the vessel captain to steer-to navigate, to stay on course and run straight and accurate data collection lines. Lines were run as straight and on-course as conditions would allow. DGPS was accurate to within 5 feet horizontally, and 1 foot vertically. Geophysical instruments were integrated with the DGPS so that the data could be tagged with position information at regular intervals during data collection. All fieldwork and submittals reference and report horizontal locations using the Lambert Grid System for the Commonwealth of Massachusetts (Mainland Zone 2001) and NAD 1983. Positions were verified by survey in U.S. Survey Feet. Vertical data are referenced to Mean

Lower Low Water (MLLW) to match datum currently being used in Corps drawings. Results were provided in English units, to be consistent with existing Corps plans.

h. Sub-bottom Profiling. e4 mobilized to the site the appropriate seismic reflection equipment necessary to perform sub-bottom profiling of the areas. e4 selected the most appropriate equipment to provide the appropriate balance between depth penetration and resolution for the conditions within each portion of the study area. Lower frequency equipment has greater depth penetration, but lower resolution while higher frequency equipment gives higher resolution, but does not penetrate as deep. The maximum dredge depth considered was -55 MLLW (-51 MLLW including 2ft required overdredge in the case of hard bottom and additional optional 2ft allowable overdredge). Therefore, the exploration program was geared to acquire high-quality data to -60 MLLW. If acoustically opaque gas (entrapped in mud) was encountered, e4 would have had to propose extraordinary measures to penetrate the mud acoustically, but the areas that with acoustic difficulty were identified and noted.

i. Interpretation. An experienced, qualified geophysicist interpreted the geophysical data collected, and made best judgment assessments of the presence and limits (horizontally and vertically) of glacial till and bedrock within the dredging limits of the study area. Geophysicist also noted the places in the geophysical data where there was greater uncertainty in the interpretation, and other places where subsurface investigations could add the most value (at cross-points of the geophysical lines, for example). As noted, the preliminary interpretation and presentation were to been done within 3 weeks of completing the field effort. Resumes of the geophysicist(s) were submitted with e4's proposal.

2.4 Task 3a – Side-scan sonar (optional)

e4 utilized a two-orthosonograph™ approach, to determine the distribution of surface sediments, rock exposures, and the presence of utilities or obstructions. e4 used a side-scan sonar with a frequency of 440 kHz. Each orthosonograph provided 100% coverage, similar to a seamless aerial photograph-like image. The orthosonograph illuminating from the north emphasized the southern side of the area. The orthosonograph illuminating from the south emphasized the northern side of the area. Each image was calibrated through the reflection coefficients to indicate hard materials, such as rock and soft material, such as mud. The image was also able to indicate sediment type ranging from sand to mud. The side scan was able to identify the presence of a utility or obstruction or ridge on the sediment surface.

2.5 Task 4 – Seismic reflection report

e4 also submitted a detailed report, including geologic interpretation, technical evaluation of results relative to project objectives, and recorded results of subsurface exploration work to NAE in raw data form. This report was in both hard copy and in electronic form. Three (3) copies of the draft hard copy report were submitted to NAE for review and comment. Three copies of a corrected copy of the initial submission were submitted as the final submission for the project. The submittal also contained the following items:

- Discussion of equipment and methods used during field program, and explanation for any deviations from the Work Plan.

- The daily narratives of field operations as written in the field, including any additional field notes produced, and any records from the weekly safety meetings.

- Cross sections of processed seismic reflection data and geologic cross-sections with interpreted geology including organic sediments, marine sediments, glacio-marine clays, glacial tills, low RQD/low velocity bedrock and high RQD/high velocity bedrock. Nearby boring log and probe information projected onto the cross-sections.

- Full-size plans for the study areas investigated showing high-resolution bathymetry, locations of seismic lines, contoured surfaces of elevations of top of bedrock surfaces and glacial till surfaces (isopach maps) within the horizontal and vertical dredging limits. Plans depicting contoured elevations of subsurface materials interpreted to be appropriate for mechanical removal (i.e. diggable, rippable) versus those requiring blasting based upon seismic velocity, drilling observations, and laboratory rock core testing. Plans of a quality for, and at a scale suitable for, use in scoping future subsurface investigations, during design, and for incorporation in dredging plans and specifications. Additional figures were to be prepared as needed, and other figures deemed necessary and appropriate for summarizing results (dense till extent and thickness map, for example, if encountered).

- Proposed locations of borings on full-size plans with tabulated coordinates. Locations proposed by e4 were reviewed and approved by NAE.

e4 prepared a transmittal cover letter when furnishing the final submittal for this project. The letter included a statement that all comments have been addressed and incorporated and all requirements have been met.

The final submission was submitted in both electronic and paper versions. The electronic version was submitted on computer compact disk (CD) or DVD and included all raw data, tables, graphs, or text, as appropriate, including the raw geophysical data. The CD/DVD was clearly labeled with the file name and description in an orderly fashion. All text files were done in Microsoft Word. All Government-furnished material (references, reports, data, etc.) provided were returned with the Final Report.

All submittals to the Government were directed to the U. S. Army Corps of Engineers, New England District, 696 Virginia Road, Concord, Massachusetts 01742-2751, Attn: Dr. Stephen Potts.

Upon completion of the contract, all data, reports, and related materials obtained as a result of this contract became the property of the U.S. Government and were turned over to the Contracting Officer, NAE Office.

2.6 Task 5 – Drilling mobilization/demobilization

e4 planned, coordinated, prepared, procured, supplied, and mobilized to the project site the necessary resources to meet the contract requirements, including all marine drilling plant and support vessels, pilots, operators and crew, drill rig, drill crew, geologist, supplies, and equipment capable of performing the work scoped in the exposed marine conditions of the outer navigation channels.

e4 was responsible for making all Notices to Mariners and coordinating with the Coast Guard and Harbor Master.

Before beginning operations, e4 coordinated with the U.S. Coast Guard to issue a "Notice to Mariners" regarding e4's operations. The U.S. Coast Guard point-of-contact for this project is as follows:

Commander Jason Smith, Chief, Prevention Department
Officer-in-Charge, Marine Inspection
U.S. Coast Guard Sector Boston
427 Commercial Street, Boston, MA 02109
Telephone 617-223-3032.
Email: jason.e.smith2@uscg.mil

The Harbor Master is:

Sgt. Joe Cheevers Boston Harbor Patrol Unit
34 Drydock Avenue
South Boston, MA 02127
617-343-4721

2.7 Task 6 – Boston Harbor borings

Project Background. Boston Harbor has undergone numerous phases of maintenance and improvement dredging, deepening, and widening since its establishment as a major port in the northeast. Current channel authorized navigation limits are shown in Table 7.

Table 7. Authorized elevations in the deepening project.

Channel/Reach	Current width ft	Proposed width ft	Current depth ft below MLLW	Proposed depth ft below MLLW
OUTER HARBOR:				
Broad Sound N. Entrance Channel:				
Outer Approach	1,100	1,100	40	51[a]
Main Lane (southeast)	S: 900	900	S: 40	51[b]
LOWER HARBOR:				
President Roads Channel	1,200	1,200	40	47
President Roads Anchorage	3,100	same	40	47
Main Ship Channel 2 lanes from President Roads to Reserved Channel	N: 600 S: 600	N: 300 S: 900	N: 35[c] S: 40	35 47
Main Ship Channel 2 lanes-south lane only from Reserved Channel to Ted Williams Tunnel	600	600	40	45
Reserved Channel	430	varies[d]	E end: 40 W end: 35	47 35
Turning basin	1,200	1500x1600	40	47

a. Widened at bend.
b. Widened through outer confluence.
c. Parts of north lane to be incorporated into deepened south lane 800-900 feet wide with further widening in bends.
d. Only the 35-foot upper end is 450. Other areas 430. Other areas different.

A Feasibility Study, completed in 2013, examined the alternatives for further improvements to navigation, widening and deepening the channels below the Ted Williams Tunnel as well as deepening the Chelsea River Channel and a portion of the Mystic River Channel. Previous investigations to support this study include:

- 2002 Marine Geophysics (seismic reflection)
- 2003 Subsurface Explorations (probes)
- 2010 Subsurface Explorations (borings)

Previous subsurface investigations were also done to support the 1988 Feasibility Study of deepening portions of the Mystic River, Inner Confluence area, and Chelsea River, and are summarized in the 1996 Design Memorandum for Boston Harbor. This deepening work was completed in 2001.

Maintenance dredging at Boston Harbor was performed in the Broad Sound North Channel in 2004-2005 and in the Main Ship Channel in 2008-2009 to remove shoal material and return channel bottom elevations to authorized depths. At the completion of the dredging effort, isolated high areas of ledge remained. The Corps performed an after-dredge survey, using multi-beam methods, and identified two locations in the Broad Sound North Channel and several areas in the western reach of the President Roads Anchorage where the channel was shallower than the authorized depth. This rock was removed in 2008-2009 by blasting and hydraulic hammer. After-dredging surveys in 2009 with multi-beam surveys identified thirteen (13) locations where the channel was higher than the authorized limit. The Corps further characterized the geometry and hardness of these locations using borings and side-scan sonar. Rock was removed by blasting and dredging in 2012.

Vertical Datum: The datum for this project is Mean Lower Low Water (MLLW) and is the vertical datum from which all depths and elevations are measured. In the scope, depths below MLLW are shown, and therefore negative signs are not used, but it should be understood that where an elevation is referenced to MLLW, the elevation would in fact be negative. All e4's records and submittals show the negative sign where elevations are referenced to MLLW. Where depths below MLLW are used, the negative sign was left off.

Horizontal Coordinate System: All fieldwork and submittals reference and report horizontal locations using the Lambert Grid System for the Commonwealth of Massachusetts (Mainland Zone 2001) and NAD 1983.

The geotechnical engineering services performed under this task are listed below, and described in greater detail in subsequent sections:

a. Drill and sample borings, and collect and log bedrock core. Save samples of all materials and deliver to a Corps' approved laboratory for rock mechanics testing.
b. Produce field logs of the borings (handwritten, typed and corrected), including drilling observations, boring coordinates and bottom elevations, and field classifications for all soils and rock encountered.

e4's schedule and effort included reasonable time for vessel traffic, set-up, etc. e4 sequenced executable work to minimize potential for downtime or delay where weather would have been a limiting factor. e4 coordinated the work schedule around incoming/departing ship schedules including LNG tankers and cruise ships, and any associated security requirements that may impact operations.

Drilling, sampling, and logging

a. *Datum, Coordinate System, Units.* All fieldwork and submittals reference and report horizontal locations using the Lambert Grid System for the Commonwealth of Massachusetts (Mainland Zone 2001) and NAD 1983. Vertical datum is the Mean Lower Low Water (MLLW) vertical datum. Measurements were made in feet, and tenths of feet.

b. *Survey of Locations:* Actual boring locations were measured in the field by e4, using GPS survey equipment, in such a way that sub-meter accuracy was achieved horizontally, and vertical accuracy is +/- 6 inches.

c. *Boring Locations.* e4 identified 26 boring locations following the completion of the reflection seismology survey. Under the base task order, the scope included the performance of 26 borings. All boring locations were approved by USACE considering e4's recommendations in order to provide adequate horizontal spatial coverage in areas with likely shallow bedrock. Coordinates were specified in Massachusetts State Plane Coordinates, NAD 1983.

Boston Harbor boring locations

d. *Positional Accuracy.* e4 positioned and set up the plant in such a way that actual field drilling locations were within 30 feet of the location coordinates proposed by e4 and approved by NAE. Actual boring location coordinates were recorded on the logs and also tabulated separately in the report. NAE's Survey Unit would have been consulted for any supplemental site survey information. Corps survey contacts can be reached at 978-318-8526.

e. *Boring Depth.* Borings extended to an elevation at least -55ft MLLW or deeper. Ten (10) feet of bedrock core was collected at each location. e4 maintained on-site all materials, equipment, and personnel required to perform rock coring as described herein.

f. *Drilling Qualifications.* e4 provided all labor, materials, and equipment necessary to complete the specified subsurface explorations and sampling. e4 provided well maintained and calibrated drilling and sampling equipment, and a qualified crew and driller experienced in all phases of exploration drilling, sampling, and test methods for engineering purposes. The driller has at least five years drilling experience using spun and drive casing, rock coring, and roller bit and wash boring methods in the North Atlantic region, and has a minimum of 5 years of experience operating from marine or floating plant. Resumes of the drillers were submitted with the e4's proposal.

g. *Drilling Inspector Qualifications.* e4 provided a drilling inspector trained as a geologist. The inspector is knowledgeable in the local bedrock geology, description and classification of bedrock core, visual soil classification methods of ASTM D 2488, in the Unified Soil Classification System of ASTM D 2487, in the general drilling procedures to be used for this project, rock coring in accordance with ASTM D 2113, and in the performance of subsurface drilling operations and rock coring from a marine plant. The inspector has at least 5 years of experience in this type of work. Resume(s) of the drilling inspector(s) were submitted with e4's proposal. The inspector performed field inspection, developed field exploration logs, classified samples, performed quality control, recorded the daily operations of the drill crew, and performed other recording and coordination duties as required including a daily safety meeting. The inspector had no other duties other than the inspection work described. No member of the drilling crew performed the inspection function in addition to their drilling crew duties. No drilling work or other fieldwork of this project, other than mobilization and demobilization, was performed in the absence of the inspector. The inspector was NAE's primary point-of-contact for this project. e4 provided the inspector with a cellular telephone or equal means of communication so that contact with NAE was possible during all work hours.

h. *Casing.* All borings used a 4-inch minimum diameter steel casing, and casing was seated into the top of bedrock sufficiently to allow rock coring, but no deeper than necessary, in order to ensure collection of rock from the uppermost zone of bedrock.

i. *Rock Coring.* Rock coring was performed using an NX or NQ-size double-tube swivel type 5-foot core barrel, in accordance with procedures in ASTM D 2113. Rock coring operations were conducted in a way to maintain integrity of core, minimize disturbance and breakage from coring operations, and maximize recovery. Use of split core barrels are preferred.

j. *Minimum Acceptable Recovery.* For each boring, a minimum of 80% core recovery is required. Borings with core recoveries of less than 80% were offset and re-drilled. If the second attempt also recovers less than 80%, then the boring will be accepted (as complete), and no further attempts will have been required.

k. *Bedrock Core Logging and Documentation.* Bedrock core was logged, in terms of rock type, hardness, structure, degree of weathering, mineralization, discontinuities (angle of inclination measured from horizontal, planarity, roughness, aperture, infillings, coatings, mineralization, etc.). Percent recovery and Rock Quality Designation (RQD) was calculated in the field and recorded on the boring logs. Mechanical breaks were noted both on the core and on the logs. Core was marked with vertical stripes to allow pieces to be replaced in proper orientation. Core was securely placed in sturdy, wooden, or equivalent, core box, and boring number, date, core run numbers, recovery, and RQD were recorded on the attached core box cover. Wet core was photographed, to include the information on the core box cover, and a scale. Spacers, such as wooden blocks, were used to mark between core runs, zones of core loss, and to secure the core against shifting during transport. The procedures of ASTM D 5079 for the preservation and transportation of core samples were followed.

l. *Field Boring Logs.* The drilling inspector assigned to this project kept detailed field logs of the borings. Logs were filled out on a daily basis such that each day of drilling activity was fully recorded at the end of work for that day. The field logs were produced using the Corps form (ENG Form 1836 and 1836-A) to have been provided separately, or one proposed by e4 in the work plan and approved by NAE. Field boring logs have a minimum scale of one inch equals one foot, to allow sufficient room for material descriptions. Field logs were completely filled out in the field, at the time of drilling and sampling, with classifications, drilling observations, the start and finish clock times for each core run, drill times (minutes per foot), and drill fluid losses. Logs included at a minimum: dates, boring numbers, location, driller and inspector names, drilling details and methods used, and listed by depth, sample number, core run number, classifications (including ASTM descriptions, moisture levels, color, density, estimated percentage of major and minor components), strata breaks, blow count data for sample and casing drives, casing depths, sample recoveries, and other pertinent details of the drilling operations. The inspector also recorded coring bit type and condition. During rock coring the inspector recorded rig operations (down pressure, wash water pressure, core barrel rotation), coring rate (minutes per foot), and drilling observations (rough drilling, chatter, rod drops, drill fluid, etc.) and any drilling fluid loss, location and quantity. e4 recorded depth information on the boring logs so that the 0.0-foot depth coincided with the channel bottom; corrections for water depth, tidal fluctuations, and measurements in the field were performed to accomplish this. e4 recorded the clock time at the start of and completion of each core run, so that tide level could be determined from the nearest tide gauge, as a back-up to other methods, to confirm water elevation at the time of drilling. All final elevations on the logs are in MLLW. All field logs and records were preserved in good reproducible condition and were available for examination by the NAE Representative throughout the field work. Separate detailed field logs were made for each exploration.

m. *Field Submissions.* Copies of the field boring logs were submitted to NAE on a weekly basis. In addition to the field logs, a short narrative was written by the inspector describing each day's activities as related to actions taken and work completed. These Progress Reports were submitted daily to NAE, via e-mail or FAX. Copies of the daily written Progress Reports were included in the Report of Explorations.

n. Where overburden was found to be present overlying bedrock, then continuous soil sampling methods were used to sample the material until bedrock was reached. Total depth of the boring needed to reach elevation to at least -55ft MLLW. Soil sampling was in accordance with Standard Penetration Test (SPT) procedures as specified in ASTM D 1586, except that a 300-pound hammer, an 18-inch drop, and a 2.5-inch inside diameter split sampling spoon was used due to the anticipated soil conditions. Visual classification of soil samples retrieved from the sampling spoon were performed by the drilling inspector in accordance with ASTM D 2488 and the Unified Soil Classification System. Refusal of the sampling spoon for the purposes of this project is defined as 100 blows per 6 inches of penetration, or bouncing refusal. Bedrock was cored upon reaching refusal.

o. Rotary auger and Odex drilling methods were not permitted on this project. All borings were advanced by roller bitting and wash methods and rock coring, as appropriate.

p. *Samples.* e4 saved and labeled representative samples of each material encountered while sampling. e4 supplied all sample jars, labels, and core boxes required for the preservation of samples. Core boxes were constructed of lumber or plywood with operating latches and were labeled properly. Material was collected in 8 oz. minimum jars or in sufficient quantity to allow performance of subsequent laboratory soil tests, including grain size analysis and hydrometer tests. All jar samples had the boring and sample identification written on both the lid and a label on the side of the jar, using indelible ink pen or marker. All samples were delivered to the Corps' laboratory (to have been identified prior to Notice to Proceed). For planning purposes, e4 assumed the Corps' laboratory is located in Acton, MA.

q. e4 kept on the job sufficient marine plant, support vessels, and equipment to meet the requirements of the work. The marine plant was made available prior to the Notice to Proceed such that it could be inspected by an NAE representative for quality assurance activities. The marine plant and equipment was in satisfactory operating condition and was capable of safely and efficiently performing the work in the depths of water defined above. The floating plant and equipment was subject to inspection by NAE at all times. No reduction in the capacity of the marine plant and equipment employed on the work was made except by written permission of the Contracting officer. Prior to commencement of work at the site, e4 made available to NAE for review copies of all applicable inspections and certifications of marine plant and equipment as required by EM 385-1-1, the U.S. Army Corps of Engineers Safety and Health Requirements Manual, as well as Federal, State and local laws and regulations.

2.8 Task 6A – Soil Borings (Perform five additional) (optional)

The requirements cited in Task 6 apply to these five (5x) additional borings. It is also understood that these borings were to be exercised (if required) in sufficient time so that they may be performed before the commencement of the Task 6 drilling operations. This task is executable up to 6 times.

2.9 Task 6B – Soil Borings (Perform one additional) (optional)

The requirements cited in Task 6 apply to these one (1x) additional boring. It is also understood that these boring were to be exercised (if required) in sufficient time so that they may be performed before the commencement of the Task 6 drilling operations. This task is executable up to 6 times.

2.10 Task 7 – Rock mechanics testing and report (optional)

The field inspector assessed bedrock cores for rock mechanics testing throughout the course of the drilling work, and select intervals for testing during the field program.

The following rock mechanic tests were performed on bedrock core from each boring location (Table 8).

Table 8. Required sample analyses.

Test	Number per Core Location	Total Number of Tests
Unconfined Compressive Strength w/ Young's Modulus (ASTM D7012, Method D, and ASTM D 3148; core preparation by ASTM D 4543)	1	26
Point Load Index (ASTM D 5731)	1	26
Splitting Tensile Strength (Brazilian)(ASTM D 3967)	1	26
Total Hardness	1	26
Unit Weight & Classification	1	26
Petrographic Analysis (ISRM procedures)	1	26
Acoustic Velocity	1	26

Rock mechanics testing was conducted at a Corps-approved laboratory. As part of the proposal e4 identified the proposed laboratory for the testing.

Interim report. e4 submitted a preliminary interim report presenting, tabulating, and summarizing the rock mechanics testing results. In this report, e4 used the findings from the testing to evaluate and make recommendations.

2.11 Task 8 – Boston Harbor report of explorations (optional)

e4 prepared this comprehensive report of explorations to present and summarize the field effort, and any deviations from the Work Plan. This report includes Weekly Safety Meeting logs, Daily Progress Report (Appendix I), final checked boring logs (Appendix II), and a tabulation of actual (GPS surveyed) boring locations, elevations of channel bottom, depth drilled, completion depth and elevation of each boring location, length of rock cored, % recovery, RQDs, photographs of cores, and a figure showing the actual boring locations.

Final electronic typed logs will be generated in gINT v.8. Corps will provide the data template and libraries. Electronic files will be provided to NAE upon completion.

In this report, e4 used the findings from the seismic survey, rock mechanics testing, and boring program to evaluate and make recommendations regarding the appropriate rock removal methods required for each location, specifically whether the rock at each location requires blasting, or if it can be removed by other mechanical means (ripper, hydraulic percussive methods, such as a hoe ram, etc.).

The final submission was submitted in both electronic and paper versions. The electronic version was submitted on computer compact disk (CD) or DVD and included all drawings, tables, graphs, and text, as appropriate. The CD/DVD was clearly labeled with the file name and description in an orderly fashion. The CD/DVD included the individual electronic native files (Word, Excel, MicroStation, gINT, etc.) All text files were done in Microsoft Word. In addition, an electronic version was submitted as one consolidated file in PDF format (Adobe Acrobat, most current version), including scanned copies of the original field logs.

2.12 Task 9 – Weather day, multi-executable (optional)

This option covered a single Weather Day and it covered the costs associated with marine plant and personnel in a non-working mode on a day due to weather conditions making it infeasible and/or unsafe to perform required work. This option was multi-executable up to 15 times.

e4 telephoned the Corps (Dr. Stephen S. Potts at 978-318-8311 and Peter Hugh at 978-318-8452) immediately when weather conditions potentially prohibited work. e4 requested approval for use of a Weather Day, and followed up with a submittal formally documenting the conditions when weather made water work unsafe and/or infeasible.

3.0 Methodology

3.1 Task 1 – Work plan

Appendix I contains the Work Plan. The work plan includes the Tidal Plan, the Accident Prevention Plan (APP), the Health and Safety Plan (HASP), the Activity Hazard Analysis (AHA), and the Quality Control Plan (QCP).

The tides in Boston Harbor range 9 to 10ft. e4 used Real Time Kinematic (RTK) GPS in every phase of the explorations. The RTK GPS records a xyz event every second with an accuracy around 0.1ft. e4 monitored tides using the RTK GPS system on board the *RV Time and Tide* and on the high accuracy systems on board the L/B Vision.

The Activity Hazard Analysis (AHA) describes the e4 visualization of the difficulties to have encountered in the explorations. The Accident Prevention Plan (APP) describes the steps that e4 planned to resolve these difficulties in an expeditionary and safe manner. The HASP outlines pertinent site-specific safety contact and location information, and the general principles that guide e4 crews to complete operations without accident, incident, or near misses. The QCP plan outlines the steps taken to ensure highest quality result. Quality control benchmarks occur throughout every phase of mobilization, acquisition, processing, interpretation, and reporting.

3.1.1 Multi-beam bathymetry

On October 9, 2014, e4 received a composite multibeam bathymetry that USACE-NAE acquired from 2005 to 2011 (Figure 7). Most of the data was from 2009. On April 16, e4 received multibeam bathymetry that USACE-NAE acquired in 2012 (Figure 8). From January 14 to April 30, e4 received multibeam bathymetry that the USACE acquired in 2014 (Figure 9).

Each of the data sets is partial. e4 processed and created a data set to create a representation composed of the most recent point available for each location in the map. The resolution is 3ft by 3ft. The value is the average value. The horizontal datum is Massachusetts State Plane Mainland NAD83. The vertical datum is NAVD88.

3.2 Task 2 – Mobilization of seismic vessel

Time and Tide Geophysical Research Vessel traveled from Liberty Landing in New Jersey to Boston Harbor's Constitution Marina in November of 2014. The *Time and Tide* is 60ft in length and fully-equipped for geophysical exploration in shallow (<300ft) waters. Figure 10 shows the *Time and Tide* in the Main Ship Channel in the Reserved Channel area.

3.3 Task 3 – Geophysical measurements

Figure 10 contains photographs of the geophysical survey boat and the drilling lift boat used in the investigation. Two local captains were employed to supplement the e4 geophysical measurement team. These captains were familiar with commercial operations in the harbor, and each had a strong environmental awareness. There were no injuries, accidents, or near misses during the acquisition of geophysical and geotechnical data for this project.

3.3.1 Sub-bottom reflection seismology

e4 used an Edgetech 512i for all seismic data acquisition. e4 implemented a 1-10kHz chirp for roughly 75% of sub-bottom tracklines, and a 0.5-6kHz chirp for the other 25%. Sub-bottom profiling works similar to single-beam bathymetry. The much lower frequency seismic waves, however, penetrate the mudline and reflect off the strata in the subsurface. The 1-10kHz chirp penetrated through the Holocene and Pleistocene into rock. The 0.5-6kHz chirp had similar results but was particularly useful to define the top of Pleistocene when covered by Holocene silts. The sub-bottom reflection seismology provided cross sections of the strata and scour surfaces in the Holocene and Pleistocene sands. Sub-bottom seismic was also crucial for the efficient placement of geotechnical borings. Appendix III contains reflection seismic data.

Figure 11 plots the sub-bottom tracklines.

Over 1100 seismic lines were acquired. The line spacing between long lines parallel to the channel toes was 80ft. The line spacing for the cross lines normal to the channel toes was 400ft. In the deepest area, near the confluence of the Broad Sound North Channel and the Main Ship Channel in President Roads Anchorage, line spacing was decreased to 50ft. in the direction parallel to the channel.

e4 has developed a proprietary set of protocols for processing high-frequency, shallow water, reflection seismology for determination of sediments and rock in harbors.[7] e4 filters every line. e4 processes the seismic lines using wave-equation migration. Every seismic section is migrated according to a velocity model derived from the ultrasonic velocities as a first approximation for the development of a layer model, this layer model varies horizontally and vertically. Then thereafter, we iteratively improve a layer model based on focusing and defocusing of diffractions in each layer in the image. Separate velocity models were employed for the 1-10kHz and 0.5-6kHz datasets. The processing generates six images for every line. The six different images help in closing down on the interpretation.

The definition in this data was usually high. e4 encountered difficulty in the PRA due to the thickness of silt, which was as thick as three feet. Even if the degradation, the fidelity was high enough to complete the surface within the dredging prism. The 0.5-6kHz chirp helped delineate the top of Pleistocene in the PRA.

3.3.2 Task 3A Orthosonographs

e4 used an Edgetech 4200 at 400kHz to produce the orthosonographs. The side-scan sonar transmits ultrasonic waves obliquely into the water and measures the amplitude of the backscatter from the seafloor as a function of range. The reflectivity is a function of the seafloor roughness and the sediment acoustic properties. The e4-proprietary processing produces two independent orthosonographs: one insonified from the east and one from the west. These reflectivity images produce a high-definition picture of the structures on the seafloor. These images are also the best means to map debris on the seafloor.

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[7] William Murphy III, W. Bruce Ward, Beckett Boyd, Gary Fleming, William Murphy IV, Richard Nolen-Hoeksema, Matthew Art, and Daniel A. Rosales, High-resolution shallow geophysics and geology in the Hudson-Raritan Estuary Ecosystem Restoration, New Jersey, The Leading Edge, February 2011, Vol. 30, No. 2 : pp. 182-190.

All lines were acquired parallel to the channel. The line spacing was 80ft. In the deepest area near the confluence of the Broad Sound North Channel and the Main Ship Channel in President Roads Anchorage the line spacing was decreased to 50ft. to ensure significant overlapping coverage.

The side-scan images produced 100% coverage with 200% redundancy and 400% overlap of the area of investigation. The two independent orthosonographs insonified from two directions suffice to constitute the 200% redundancy. Orthosonographs are seamless aerial-photograph-like images that are insonified from one direction only. In fact, the data required to produce two images constitutes significantly greater overlap.

3.4 Task 4 – Report on seismic exploration

e4 hosted Stephen Potts, USACE-NAE, on the *Time and Tide* geophysical research vessel and the *LB Vision* drill ship.

The report on seismic exploration is incorporated in this comprehensive report. e4 organized and participated in a progress meeting at USACE-NAE on January 30, 2015. The purpose of the meeting was to convey the preliminary results and determine with USACE-NAE the nature of the reporting. It was decided that two reports would be filed: (a) an interim preliminary report for official use only, and (b) this comprehensive report including the boring report, the sample analyses, the seismic results and the integrated maps.

3.5 Task 5 – Mobilization of drill rig

Due to the significance of the tidal variation and the exposure of much of the area to offshore swell, e4 employed a lift-boat as the drilling platform. The L/B Vision was outfitted with a track-mounted CME-55 drill rig.

To best locate boring placement sub-bottom reflection seismology was employed to optimize the boring locations in the most efficient way to benchmark areas of high rock.

One call – dig safe was notified of all boring locations prior to drilling. Because the as-built location of utilities in marine environments is notoriously uncertain, and because these utilities exist in a dynamic environment, e4 is cautious and utilizes geophysical data to supplement the one call process.

In order to identify utilities and ferromagnetic obstructions to drilling, e4 measured local anomalies in the Earth's magnetic field using a Geometrics 882 cesium magnetometer with a depth sensor and altimeter. The magnetometer was towed at least 100ft behind the boat and 5-15ft above the channel floor. The data was evaluated line by line. The evaluation removed any measurement artifacts. The data was gridded using triangulation with linear interpolation. This data was used internally to ensure that no utilities existed in planned boring locations.

3.6 Task 6 – Drilling standard penetration test borings

e4 performed and completed twenty six (26) Standard Penetration Test borings. Appendix II lists the boring descriptions. Appendix II also contains sample analyses for each boring. Table 9 lists the planned locations. Table 10 lists the actual borings, their location, and distance from the planned location.

e4 supervised all drilling and sampling, as well as described and photographed all samples and cores. e4 selected samples for geotechnical testing. Aquifer Drilling and Testing (ADT) performed the drilling operations. Figure 12 contains a photograph of e4 drilling in the Main Ship Channel in the Reserved Channel area.

e4 communicated with all local facilities including the Deer Island Wastewater Treatment Plant, and requested one calls in order to identify all local utilities. e4 communicated with the Logan Airport, Coast Guard, Harbor Master, the local ship traffic to ensure safety, and the Lobsterman Associations that operate in the area. Drilling operations commenced once the utility markouts and safety were deemed satisfactory. Drilling operations proceeded under the assumption that not all utilities had been identified, and caution was used throughout operations.

Table 9. Planned boring locations determined by e4 based on geophysical survey.

Boring	Easting	Northing
	MMSP, NAD83, ft	
FD14-01	813,673.0	2,960,603.0
FD14-02	812,377.0	2,959,622.0
FD14-03	813,075.0	2,958,557.0
FD14-04	810,718.0	2,954,729.0
FD14-05	809,606.0	2,954,317.0
FD14-06	809,185.0	2,953,341.0
FD14-07	809,825.0	2,953,220.0
FD14-08	786,478.0	2,951,172.0
FD14-09	801,512.0	2,949,424.0
FD14-10	800,456.0	2,950,460.0
FD14-11	796,863.0	2,949,657.0
FD14-12	798,572.0	2,947,462.0
FD14-13	798,446.0	2,948,356.0
FD14-14	798,626.0	2,948,718.0
FD14-15	792,110.0	2,947,595.0
FD14-16	791,667.0	2,947,388.0
FD14-17	791,578.0	2,947,932.0
FD14-18	791,340.0	2,948,045.0
FD14-19	788,442.0	2,950,784.0
FD14-20	787,706.0	2,951,201.0
FD14-21	787,106.0	2,951,406.0
FD14-22	786,995.0	2,950,804.0
FD14-23	797,120.0	2,948,868.0
FD14-24	796,902.0	2,949,946.0
FD14-25	785,227.0	2,952,484.0
FD14-26	784,468.0	2,952,908.0

Table 10. Overview of core boring acquisition.

Date	Boring/Event	Easting	Northing	Distance from plan
		MMSP, NAD83, ft		ft
2014.11.23	Final mobilization			
2014.11.24	FD14-19	788,441.3	2,950,781.9	2.2
2014.11.25	FD14-01	813,676.0	2,960,595.2	8.4
2014.11.25	FD14-07	809,822.3	2,953,217.9	3.5
2014.11.26	Weather day at airport request			
2014.12.01	FD14-25	785,226.9	2,952,481.6	2.4
2014.12.02	FD14-20	787,700.7	2,951,198.4	5.9
2014.12.03	FD14-22	786,993.2	2,950,809.5	5.8
2014.12.03	FD14-26	784,474.2	2,952,908.4	6.2
2014.12.04	FD14-03	813,065.2	2,958,558.8	10.0
2014.12.05	FD14-21	787,106.4	2,951,395.4	10.6
2014.12.08	FD14-18a	791,343.4	2,948,049.0	5.2
2014.12.08	Equipment repair			
2014.12.09	Weather day			
2014.12.10	FD14-18b	791,341.2	2,948,043.0	2.3
2014.12.10	FD14-17	791,574.0	2,947,927.8	5.7
2014.12.11	FD14-15	792,108.6	2,947,589.6	5.6
2014.12.11	FD14-16	791,668.2	2,947,381.6	6.5
2014.12.12	FD14-02	812,377.4	2,959,626.0	4.0
2014.12.13	FD14-04	810,721.4	2,954,735.4	7.2
2014.12.13	FD14-06a	809,186.5	2,953,344.1	3.4
2014.12.15	FD14-06b	809,190.2	2,953,336.1	7.2
2014.12.15	FD14-05	809,602.6	2,954,318.1	3.6
2014.12.16	FD14-23	797,123.1	2,948,871.3	4.5
2014.12.16	FD14-24	796,901.2	2,949,945.9	0.8
2014.12.17	FD14-13	798,442.4	2,948,352.1	5.3
2014.12.17	FD14-14	798,623.9	2,948,720.7	3.4
2014.12.18	FD14-12	798,569.0	2,947,464.5	3.9
2014.12.18	FD14-11	796,866.6	2,949,656.3	3.7
2014.12.19	FD14-09	801,520.2	2,949,424.3	8.2
2014.12.19	FD14-10	800,459.6	2,950,460.2	3.6
2014.12.20	FD14-08	786,470.6	2,951,173.8	7.6
2014.12.20	Demobilization			

The borings were conducted following ASTM standard D1586 with three modifications: (1) blows per 6in were allowed to reach 100 blows, (2) a 3in split spoon was used, and (3) a 300lb hammer was with a 18”. The ASTM standard refusal is 50 blows per 6in, however local practice in the area is to use 100 blows per 6in for refusal to account for till deposits. This adds uncorrected N-values above 100.

The number of hammer drops (blows) to advance the split spoon 6in was counted and recorded.

e4 described the borings. Each split-spoon sample was opened and laid out for examination (Figure 13). The amount of recovery of in-place sediment was noted on the description logs.

Immediately upon opening the split spoon, the sample was photographed (Figure 13). The sediment was then cut in half and photographed again. Samples from each spoon were carefully selected and placed into clearly labeled plastic jars. Jars and lids were labeled with the project name, boring number, sample number, depth and number of blow counts required to advance the spoon. Visual descriptions follow ASTM D 2488. Conditions during drilling and characteristics of the sediments that affect drilling were especially noted.

Rock core was drilled using a diamond tipped rotary drill. Core was photographed immediately upon extraction from the core barrel (Figure 14). Rock type and description, Rock Quality Designation (RQD), fractures per foot, and percent recovery were recorded. The existence of joints, fractures, stratification, laminations, organic fragments, clasts, and shells together with their dimensions and frequency were recorded in the sample descriptions. The cores were boxed and transported to the e4laboraties in Sandy Hook, CT (Figure 15). Representative samples were tested for composition, ultrasonic velocity and other additional analyses.

Deck elevations of the L/B Vision were constrained using a Trimble SPS 855 GPS with a high accuracy geodetic antenna. Static GPS data was logged for at least 1 hour at each drill site. The static dataset was sent to OPUS for post correction. The resulting elevation data was accurate to 0.1ft. to 0.2ft. The deck to mudline offset was measured with a weighted tape measure before and after lowering casing.

As drilled boring locations were measured using a dual antenna GPS receiver. Offsets were measured from the primary antenna to the drill hole. A QC of this measurement was performed using the SPS 855 with bearing and range offsets.

3.7 Task 7 – Physical evaluation of cores

e4 assigned Terrasense of Totawa New Jersey, the task to perform laboratory measurements of, unconfined compressive strength, Brazilian Strength, point load, and total hardness tests. Appendix II contains the Terrasense results per boring. e4 performed the ultrasonic and xrf measurements. Appendix II contains the e4 results on ultrasonic velocities. Appendix IV contains the xrf measurements. National Petrographic Service Inc. made thin sections of the core samples. Appendix II contains images, the high-resolution scanned transmitted-light images, of the thin sections.

Table 11 is an overview of the sample analyses.

Table 11. Overview of sample analyses.

Test	Number	Units	Minimum	Maximum	Average
Total Hardness	6	(-)	30.93	55.58	40.40
Point Load - Diametric	23	psi	1,166	19,198	8,682
Point Load – Axial	23	psi	6,273	32,521	17,511
Splitting Tensile (Brazilian)	12	psi	484	3,161	1,498
Unconfined Compressive Strength	15	psi	2,790	27,130	12,382

3.7.1 Unconfined compressive strength, total hardness, point load and splitting tensile tests

Representative rock samples were delivered to Terrasense in Totowa, New Jersey where they 91625 were tested for unconfined compressive strength, rebound hardness, abrasion hardness, point load, and splitting tensile strength.

Unconfined compressive strength test followed ASTM D7012. Samples were measured, trimmed and sheared, and then strained until failure. Post failure images were taken of the samples. Total hardness is calculated by multiplying the rebound hardness by the square root of the abrasion hardness. Rebound hardness tests followed ASTM D5873. Point load tests followed ASTM D5731. Splitting tensile or (Brazilian) tests followed ASTM D3967.

3.7.2 Ultrasonics

Ultrasonic velocity measurements were performed at e4laboratories in Sandy Hook, Connecticut. e4 used Panametrics V114 1-MHz longitudinal-wave contact transducers, a Panametrics 5058PR high-voltage pulser-receiver, and a Tektronics TDS-210 digital storage oscilloscope for velocity measurements. The compressional-wave (P-wave) velocity was measured with the transducer both parallel and perpendicular to the layering in the sample, as well as across fractures where possible. Appendix II contains the ultrasonic measurements. These measurements are plotted along the boring descriptions.

Ultrasonic velocities measure fastest velocities in the sediments rock as a function of frequency and rock mass characteristics. The small sample size reduces the effect of discontinuities such as cracks and fractures.

3.7.3 X-ray fluorescence

e4 performed rock composition measurements at e4laboratories in Sandy Hook, CT. e4 used a Thermo Niton XRF GOLDD Analyzer to measure rock element compositions. This is a non-destructive process that measures elements that range from magnesium through uranium. Appendix IV contains the xrf measurements.

3.7.4 Thin sections

National Petrographic Inc. created thin sections from pieces of core samples. e4 scanned and characterized the mineralogy and fabric of the core from these samples. Appendix II contains images, the high-resolution scanned transmitted-light images, of the thin sections.

3.8 Task 8 – Comprehensive report: Mapping and integration

e4 processed each data set from the orthosonographs, the sub-bottom reflection seismology, USACE multibeam, and SPT borings independently. Then, we correlated the geophysical and sampling to produce several estimates of the Holocene sediments, the Pleistocene sediments, the Pleistocene till, and the Cambridge Argillite in the dredging prism.

e4 used the Caterpillar Handbook to characterize the rock. Dredgeability is machine and treatment dependent. The best way to estimate dredgeability accurately is to perform test digs with the machines on the rocks to be dredged. e4 used the characterization based on compressional-wave velocity and unconfined compressive strength. Fast rock is defined as a rock having a compressional wave velocity greater than 2,700m/s.

e4 uses redundant measurements to quantify all results. Each survey is calibrated in the local area with a proprietary test. All measurements are processed independently and integrated into a single geo-reference frame after processing. Redundant measurements (repeat lines or scans) quantify the precision and delineate uncertainty in the measurements. Repeat lines are not always delivered to the client, but are available for review upon request. e4 produced a series of surface maps from the bathymetry. The orthosonographs provide detailed images beyond the bathymetry. The orthosonographs are used to benchmark where the horizons mapped in seismic cross sections reach the surface. e4 produced a series of cross sections from the sub-bottom reflection seismology and mudline elevations from bathymetry. From the cross sections, we interpreted the subsurface horizons for the Holocene-Pleistocene boundary, the top of till, the top of rock, and the top of fast rock.

This final report includes a brief description of scope, methods, and results from the investigation. e4 processed each data set independently and then integrated into a single reference frame. Subsequently, we can integrate the data sets and quantify the error. e4 produced surface maps from the bathymetry. The orthosonographs provide the detailed images of the channel bottom beyond the resolution of the bathymetry. e4 produced a series of cross sections from the sub-bottom reflection seismology and mudline elevations from bathymetry. Each data set is processed independently and then integrated into a single reference frame. It is then that we can quantify the error.

3.9 Task 9 – Weather days

For both the geophysical and boring study, the weather was unusually cooperative. Only two weather days were employed during the entire geotechnical investigation. One day was spent conducting maintenance on the drill rig. On three days the weather prohibited the acquisition of geophysical data. Four maintenance days for the *Time and Tide* were necessary during the geophysical acquisition effort.

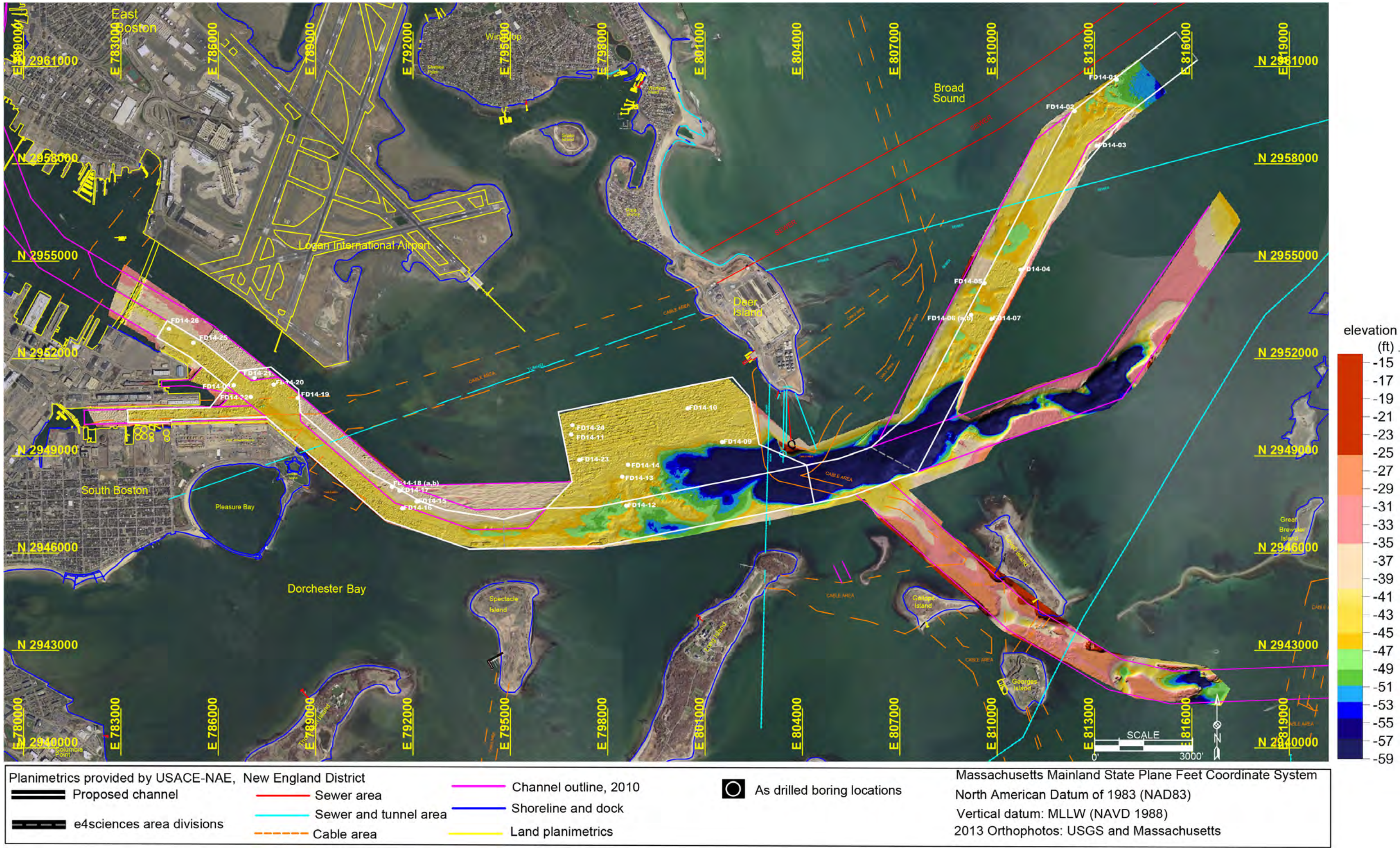


Figure 7. USACE-NAE multibeam bathymetry from 2005 to 2011.

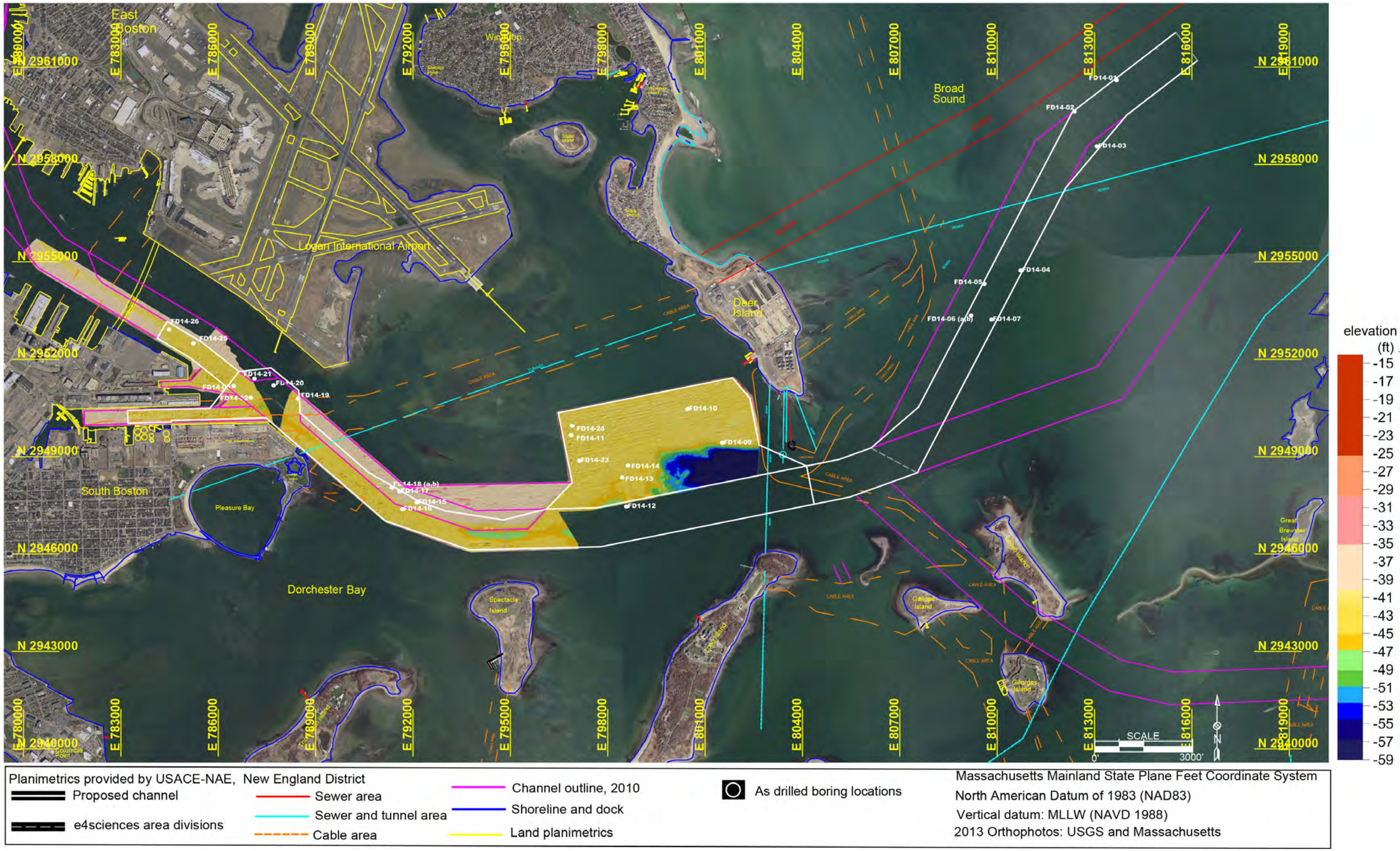


Figure 8. USACE-NAE multibeam bathymetry from 2012.

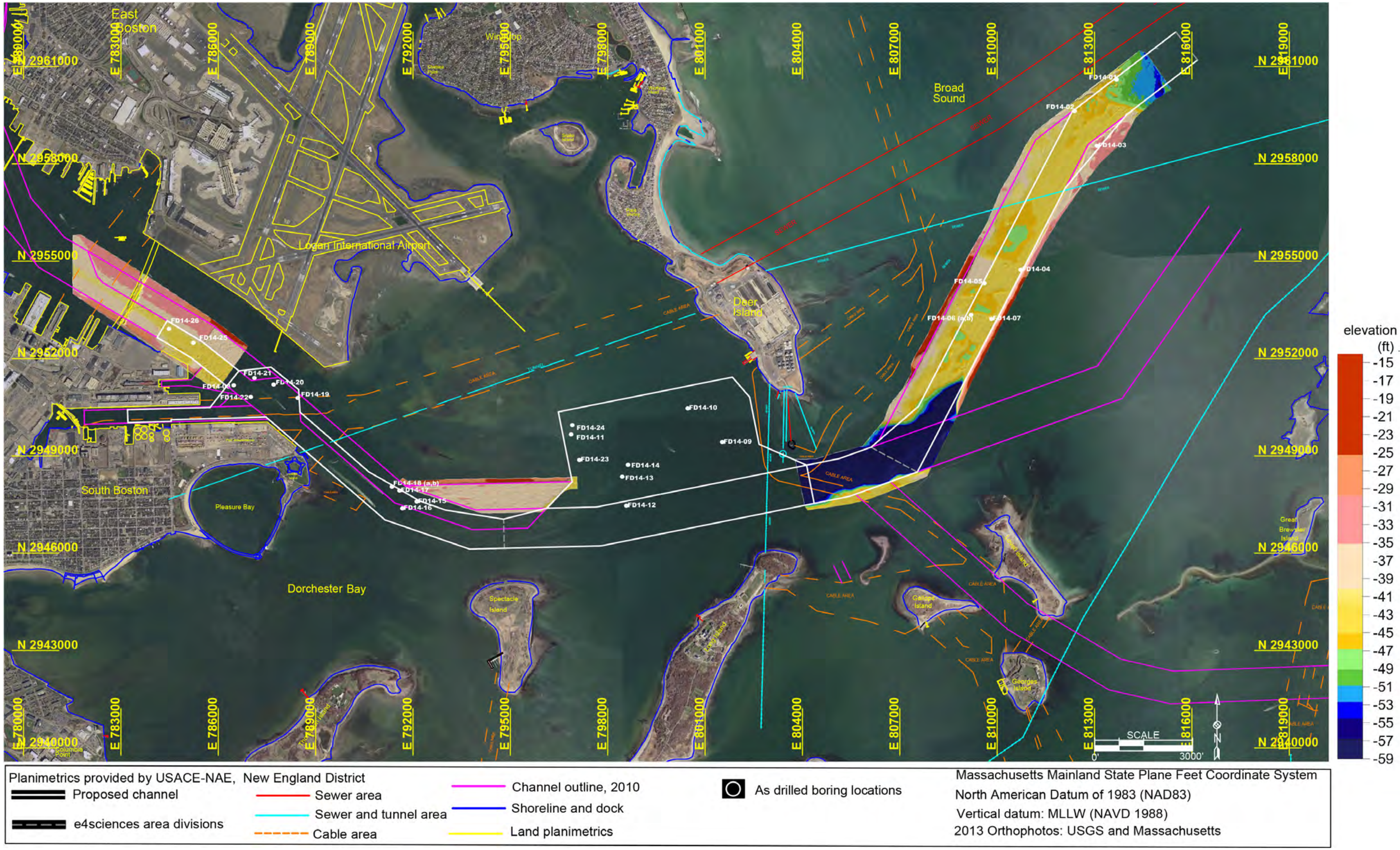
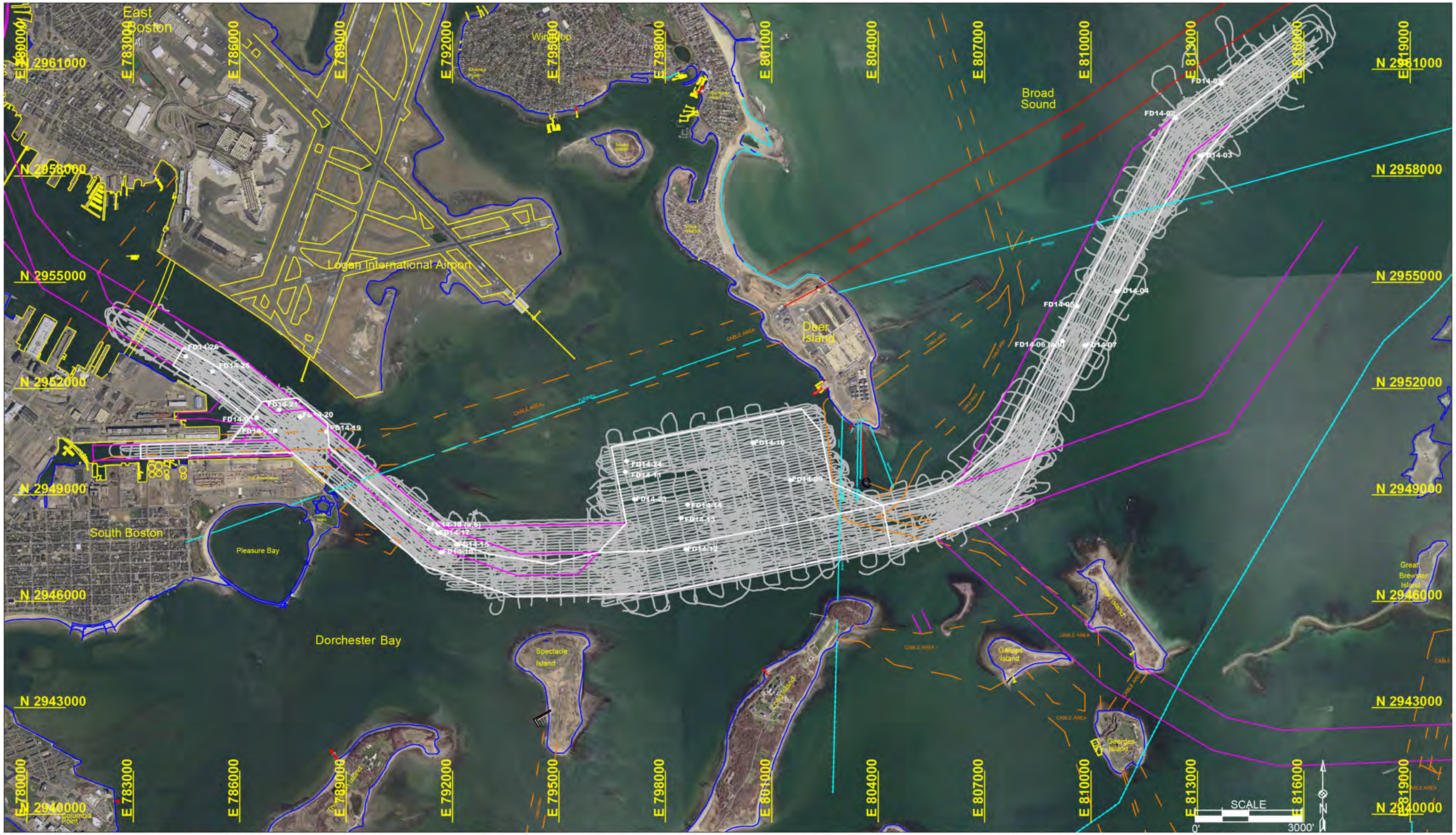


Figure 9. USACE-NAE multibeam bathymetry from 2014.

Figure 10. Photographs of (a) the Time and Tide geophysical research vessel in the Main Ship Channel, and (b) the drill rig jacked up in the Main Ship Channel.



Planimetrics provided by USACE-NAE, New England District

Proposed channel

e4sciences area divisions

Seismic tracklines

Sewer area

Sewer and tunnel area

Cable area

Channel outline, 2010

Shoreline and dock

Land planimetrics

As drilled boring locations

Massachusetts Mainland State Plane Feet Coordinate System
North American Datum of 1983 (NAD83)
Vertical datum: MLLW (NAVD 1988)
2013 Orthophotos: USGS and Massachusetts

Figure 11. Seismic tracklines from November and December, 2014.

Figure 12. Drillship operations.

Figure 13. Sediment samples photographed on the drill ship.

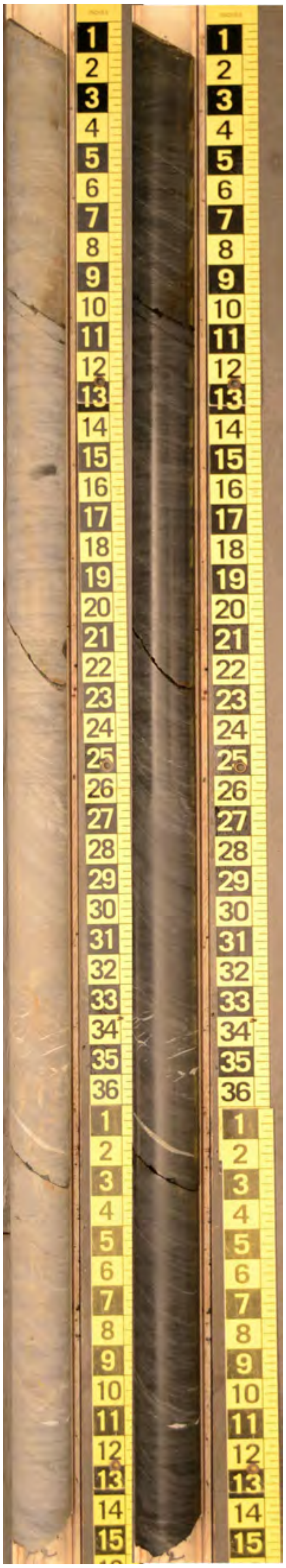


Figure 14. Rock core of Cambridge Argillite with foliation.

Figure 15. Dr. Ward examining the Boston Harbor rock cores in the e4 core laboratory.

4.0 Results

Appendix II contains the boring descriptions and sample analyses for each of the 26 borings. Figure 16 shows four examples of samples from the various sediment types obtained in the borings: Holocene silt, Holocene sand, Holocene peat, and Pleistocene Boston Blue Clay. Figure 17 shows the samples of the till and rock obtained in the borings: the clay-based till, the sand-based till, the weathered decomposed argillite, and the Cambridge argillite. The other more minor sediment and rock types are represented in Appendix II.

Figure 18 (Plate 3) maps the side-scan orthosonograph of the channel bottoms in the Harbor Deepening Project. The image maps sonar reflectivity insonified from the south. The bright spots toward white are reflective. The dark spots toward dark brown are poorly reflective. The high reflectivity arises from high backscatter from either steep facing angle or high impedance material. In the case of these images, both are evident. The overwhelming variation is due to material variation. Silt is low velocity, low reflectivity, and dark. Sand, Pleistocene sediments, and subcrops are more reflective and are brighter. Figure 19 (Plate 4) is the orthosongraph pair insonified from the north.

Figure 20 (Plate 5) plots the outline of targets for concern and instruction. Table 12 lists the targets and a brief description of each. We do not list every subcrop or lobster pot. Rather we indicate a few examples, and then trust that other objects will be self-evident.

Figure 21 (Plate 6) plots an isopach map of silt. All isopach maps in this comprehensive report plot the thickness of the material to be dredged for a given material type. The thickness of the silt, where present, is between 2 to 3ft. There is very little silt thicker than 3ft. Sand needs to be removed in North Channel. Figure 22 (Plate 7) shows the top of Pleistocene sediments. The bottom of these sediments is equivalent to the top of Pleistocene.

Figure 23 (Plate 8) shows the isopach map of Holocene sediments. Figure 24 (Plate 9) plots the top of till and rock. This is a strong interface in the seismic sections. Figure 25 (Plate 10) shows top of rock map for Cambridge Argillite formation. Figure 26 (Plate 11) plots the top of fast rock.

Figure 27 (Plate 12) shows isopach map for Pleistocene sediments. The material is Boston Blue Clay. Figure 28 (Plate 13) plots the isopach map of Holocene and Pleistocene sediments. These materials form the large majority of the volume to be removed in the Deepening Project. Figure 29 shows the isopach of Pleistocene till. Figure 30 shows the isopach map of the rock. Figure 31 shows the isopach map of fast rock.

Figure 32 shows a schematic cross section of the stratigraphy in the Harbor Deepening Project.

Table 12. Target list.

Target	Easting	Northing	Diameter	Description
	MMSP, NAD83, ft		ft	
1	783,456.06	2,954,191.60		Ted Williams Tunnel
	783,660.17	2,954,077.60		
	783,074.11	2,953,028.28		
	782,870.00	2,953,142.27		
2	783,859.87	2,950,517.27		Debris, pilings
	784,211.68	2,950,517.27		
	784,211.68	2,950,352.54		
	783,859.87	2,950,352.54		
3	783,879.62	2,950,205.74	166	Debris, pilings or pipe
4	784,345.74	2,950,294.83		Possible cable
	784,608.10	2,950,270.12		
	784,606.52	2,950,253.38		
	784,344.16	2,950,278.09		
5	784,719.65	2,950,351.47	119	Possible pilings or pipe
6	784,889.34	2,950,385.61	111	Possible cable
7	785,137.92	2,950,225.35		Possible trench scar
	785,911.65	2,950,225.35		
	785,911.65	2,950,158.12		
	785,137.92	2,950,158.12		
8	784,646.09	2,950,071.22		Subcrop ledge, Pleistocene clay & silt
	784,889.87	2,950,193.08		
	784,919.95	2,950,132.90		
	784,676.17	2,950,011.05		
9	786,506.98	2,950,300.43	438	Subcrop
10	787,396.31	2,950,789.39	546	Subcrop, Pleistocene clay & silt, silt washed out
11	788,443.35	2,949,497.34	184	Dredge marks
12	789,272.18	2,950,302.29	275	Cable, MWRA 115Kv
13	788,739.63	2,950,025.72		Cables, subcrop
	789,230.92	2,949,953.77		
	789,208.81	2,949,802.80		
	788,717.52	2,949,874.75		
14	789,210.09	2,948,819.30	91	High rock cored in 2010
15	790,367.87	2,948,845.45		Cable
	790,540.92	2,948,721.81		
	790,505.88	2,948,672.76		
	790,332.83	2,948,796.40		
16	790,876.30	2,948,459.21	314	Dredge marks at ledge
17	790,631.98	2,948,373.98	71	Dredge stick and bucket
18	790,384.37	2,948,205.65		Subcrop ledge and dredge marks
	790,793.23	2,948,205.65		
	790,793.23	2,948,024.20		
	790,384.37	2,948,024.20		
19	790,986.87	2,948,064.94	267	Subcrop, rock
20	791,241.07	2,948,264.78	159	Subcrop, rock
21	791,424.66	2,947,391.40		Subcrop, rock
	791,818.29	2,947,551.72		
	791,877.94	2,947,405.27		
	791,484.31	2,947,244.95		
22	793,167.70	2,947,198.56		Lobster pots
	793,653.52	2,947,055.71		
	793,612.29	2,946,915.49		
	793,126.47	2,947,058.34		
23	793,730.06	2,946,353.95		Lobster pots on a line, dredge cut
	794,487.19	2,946,353.95		
	794,487.19	2,946,166.74		
	793,730.06	2,946,166.74		
24	796,981.85	2,948,891.90	462	Dredge scars on subcrop pinnacles, blasted in 2008
25	803,238.76	2,948,079.52	133	
26	803,427.45	2,949,083.36	265	Pipeline and cribbing
27	804,315.39	2,949,230.82		Pipeline and cribbing
	804,395.50	2,949,263.49		
	804,499.31	2,949,009.00		
	804,419.20	2,948,976.32		

Target	Easting	Northing	Diameter	Description
	MMSP, NAD83, ft		ft	
28	806,014.81	2,949,034.76	383	Subcrop of till and debris
29	809,082.39	2,953,286.40	656	Lobster pots
30	812,116.32	2,959,239.71	225	Sand waves
31	813,958.85	2,959,686.68	518	Boulders on till subcrop
32	814,599.04	2,960,671.69	415	Grass sediments
33	790,026.70	2,948,735.87	74	Large objects

Figure 16. Photographs of various sediment samples from the borings: (a) Holocene silt, (b) Holocene sand, (c) Holocene peat, and (d) Pleistocene varved silt and clay. Scale is in inches.

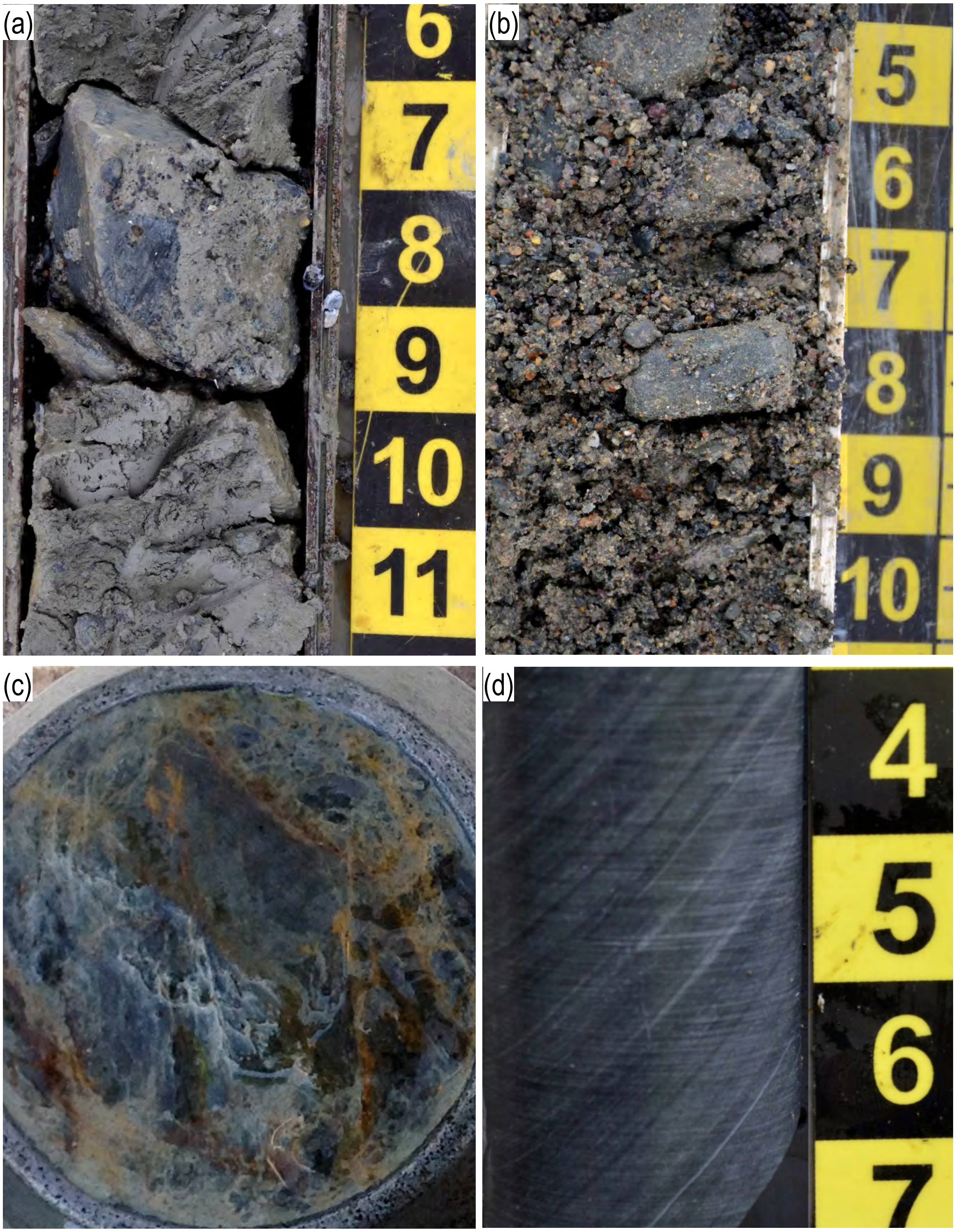


Figure 17. Photographs of examples of Pleistocene till and rock samples from the borings: (a) clay-based till, (b) sand-based till, (c) decomposed argillite in the nose of a split spoon, and (d) layered Cambridge Argillite. Scale is in inches.

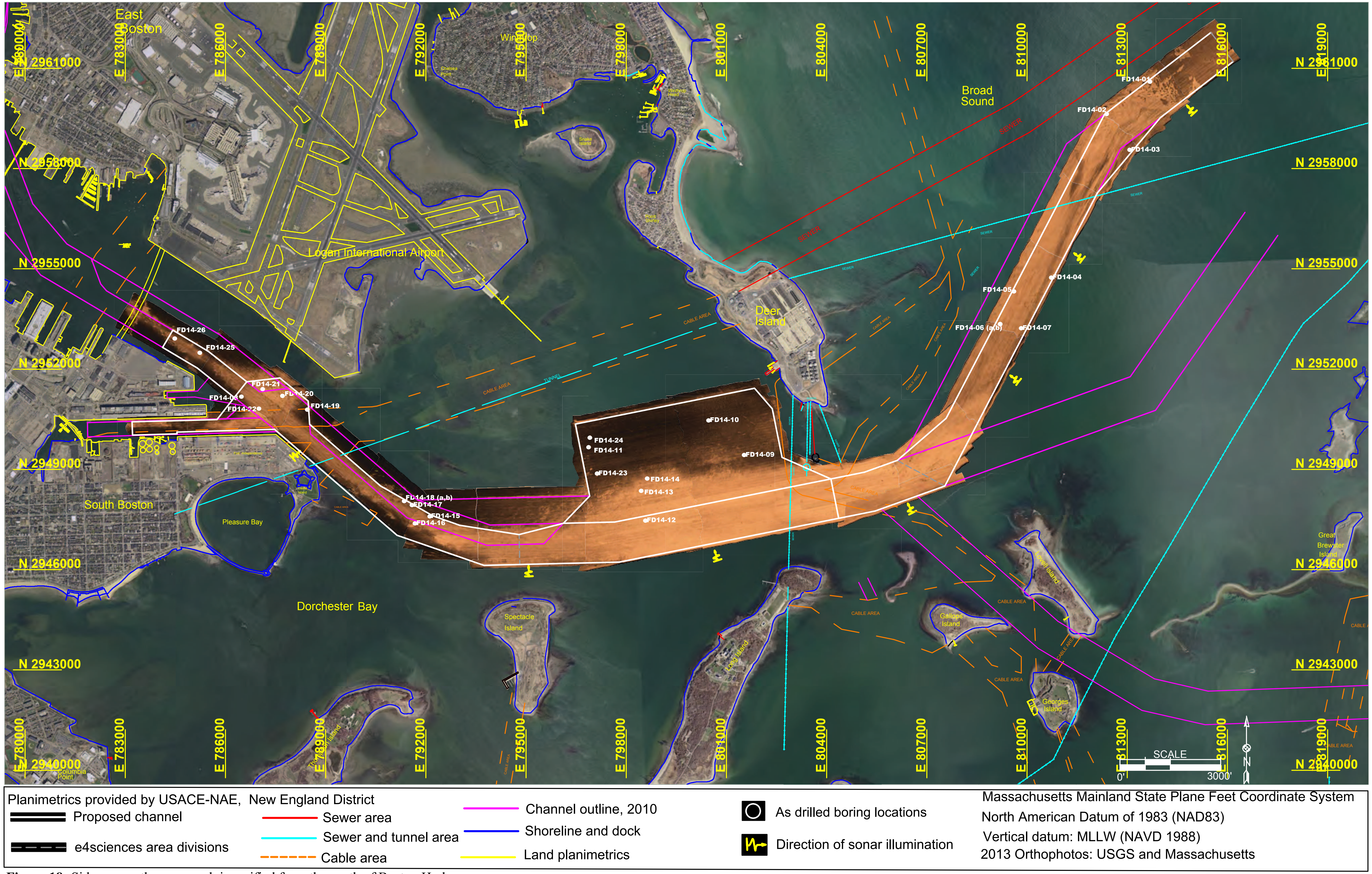
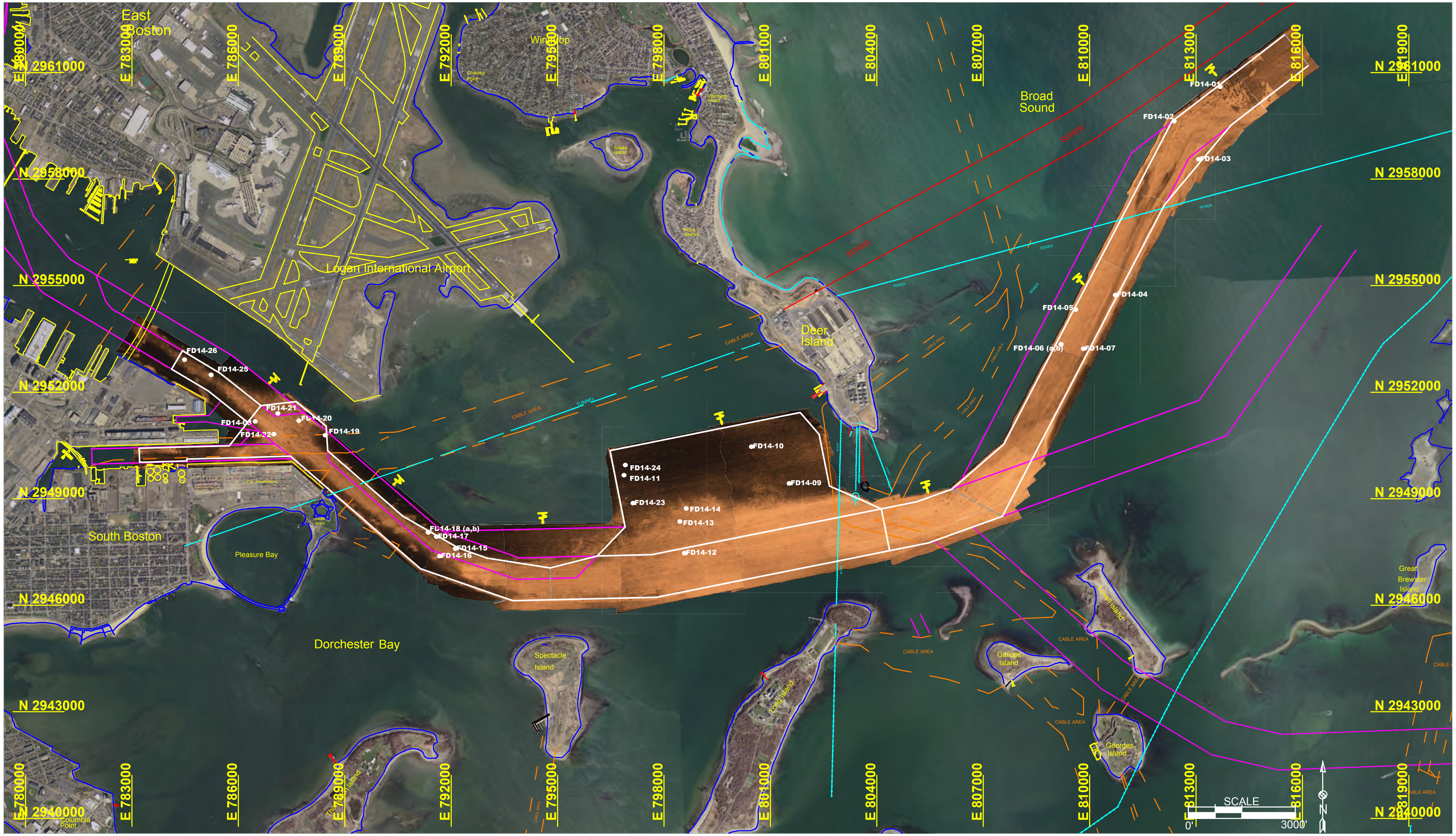


Figure 18. Side-scan orthosonograph insonified from the south of Boston Harbor.



Planimetrics provided by USACE-NAE, New England District

Proposed channel

e4sciences area divisions

Sewer area

Sewer and tunnel area

Cable area

Channel outline, 2010

Shoreline and dock

Land planimetrics

As drilled boring locations

Direction of sonar illumination

Massachusetts Mainland State Plane Feet Coordinate System
North American Datum of 1983 (NAD83)
Vertical datum: MLLW (NAVD 1988)
2013 Orthophotos: USGS and Massachusetts

Figure 19. Side-scan orthosonograph insonified from the north of Boston Harbor.

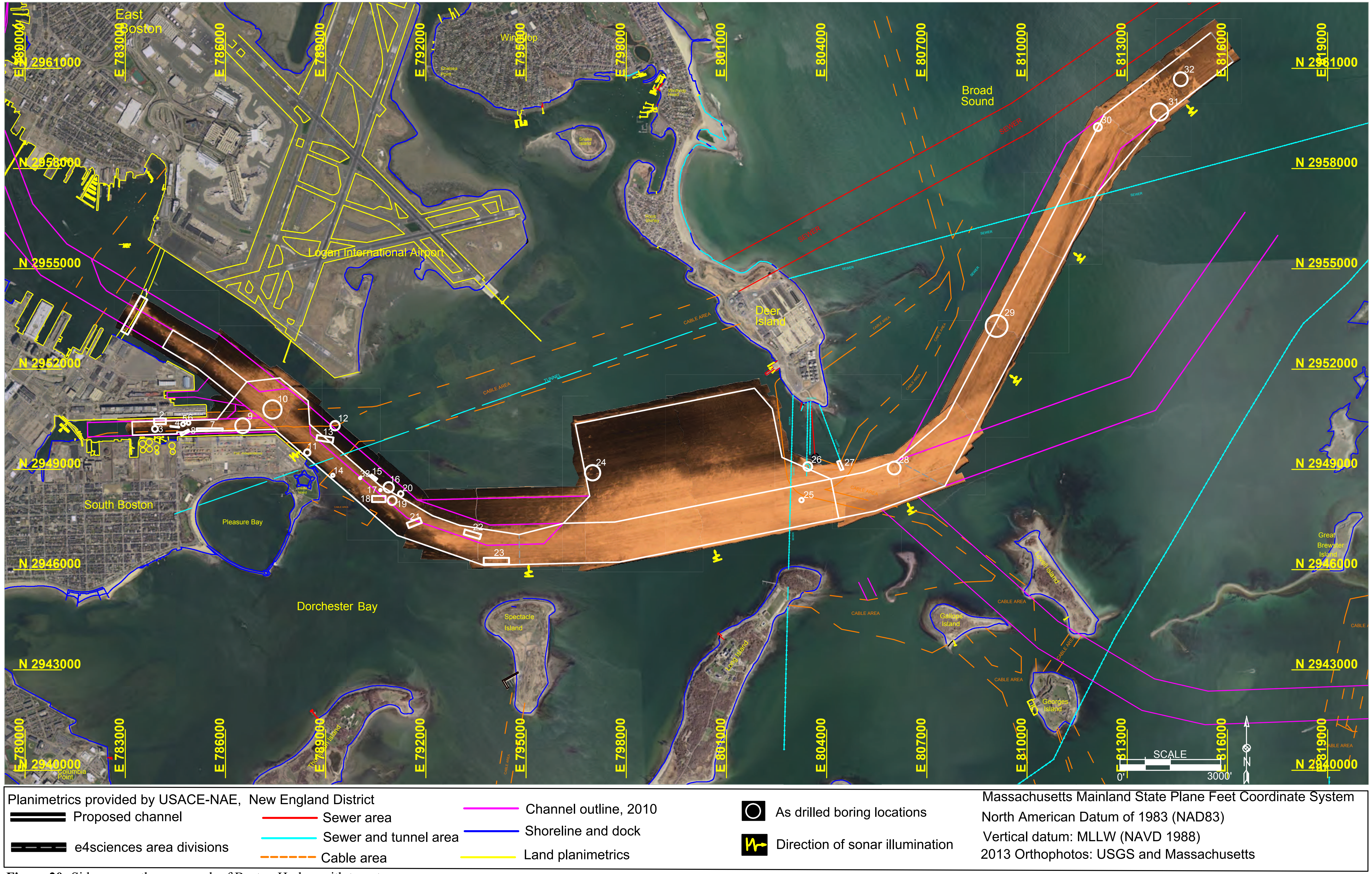


Figure 20. Side-scan orthosonograph of Boston Harbor with targets.

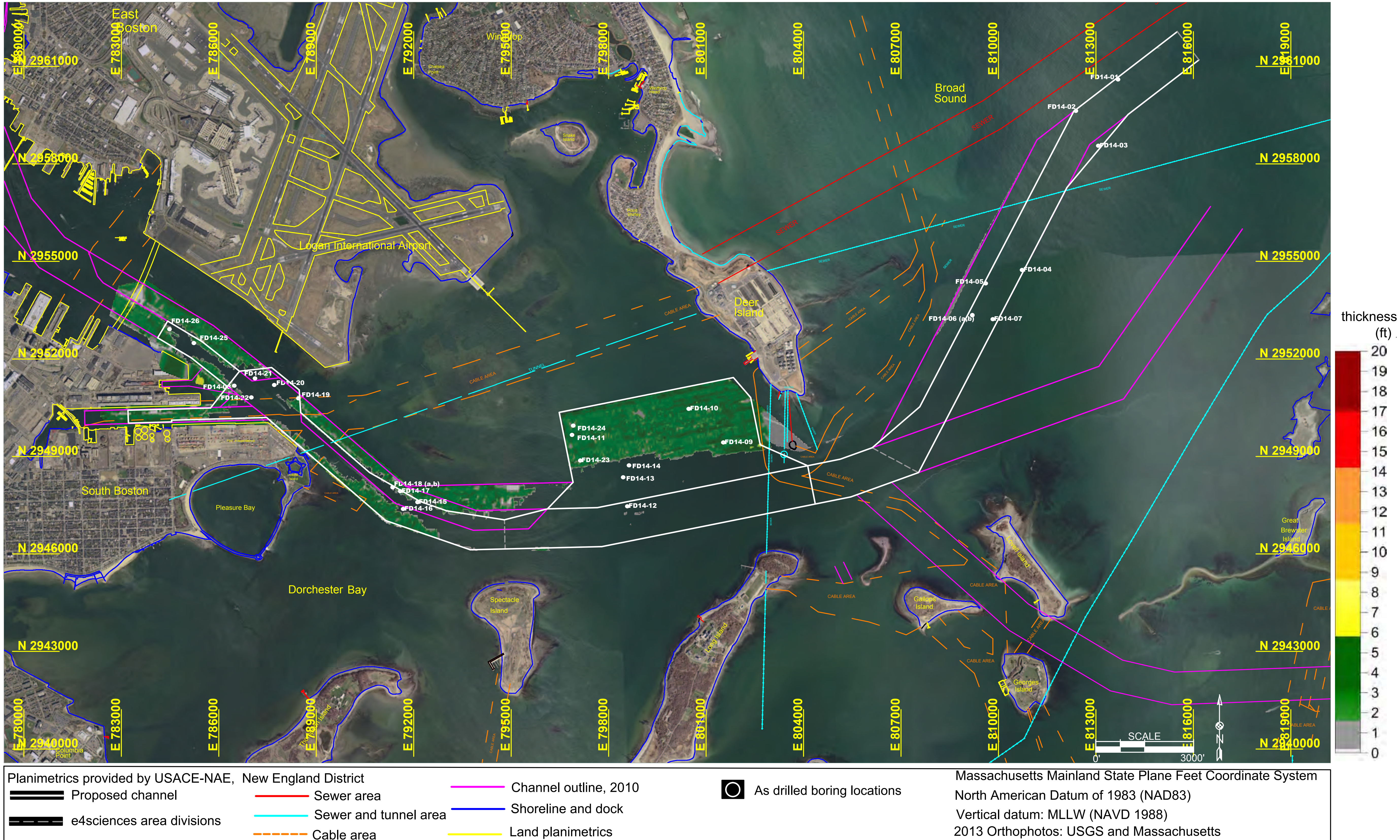
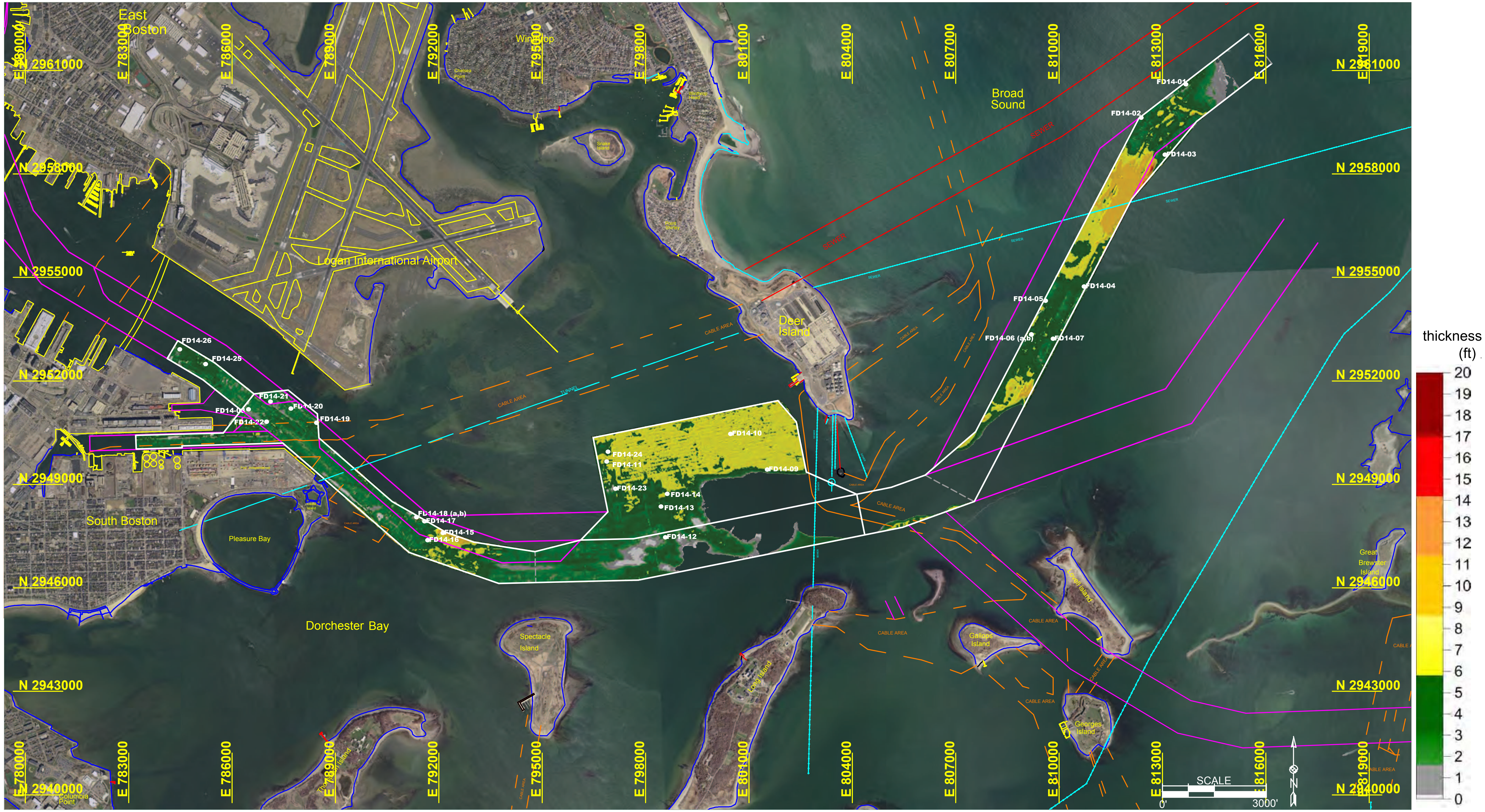


Figure 21. Isopach map of black silt.



Planimetrics provided by USACE-NAE, New England District

Proposed channel

e4sciences area divisions

Sewer area

Sewer and tunnel area

Cable area

Channel outline, 2010

Shoreline and dock

Land planimetrics

As drilled boring locations

Massachusetts Mainland State Plane Feet Coordinate System

North American Datum of 1983 (NAD83)

Vertical datum: MLLW (NAVD 1988)

2013 Orthophotos: USGS and Massachusetts

Figure 22. Isopach map of Holocene.

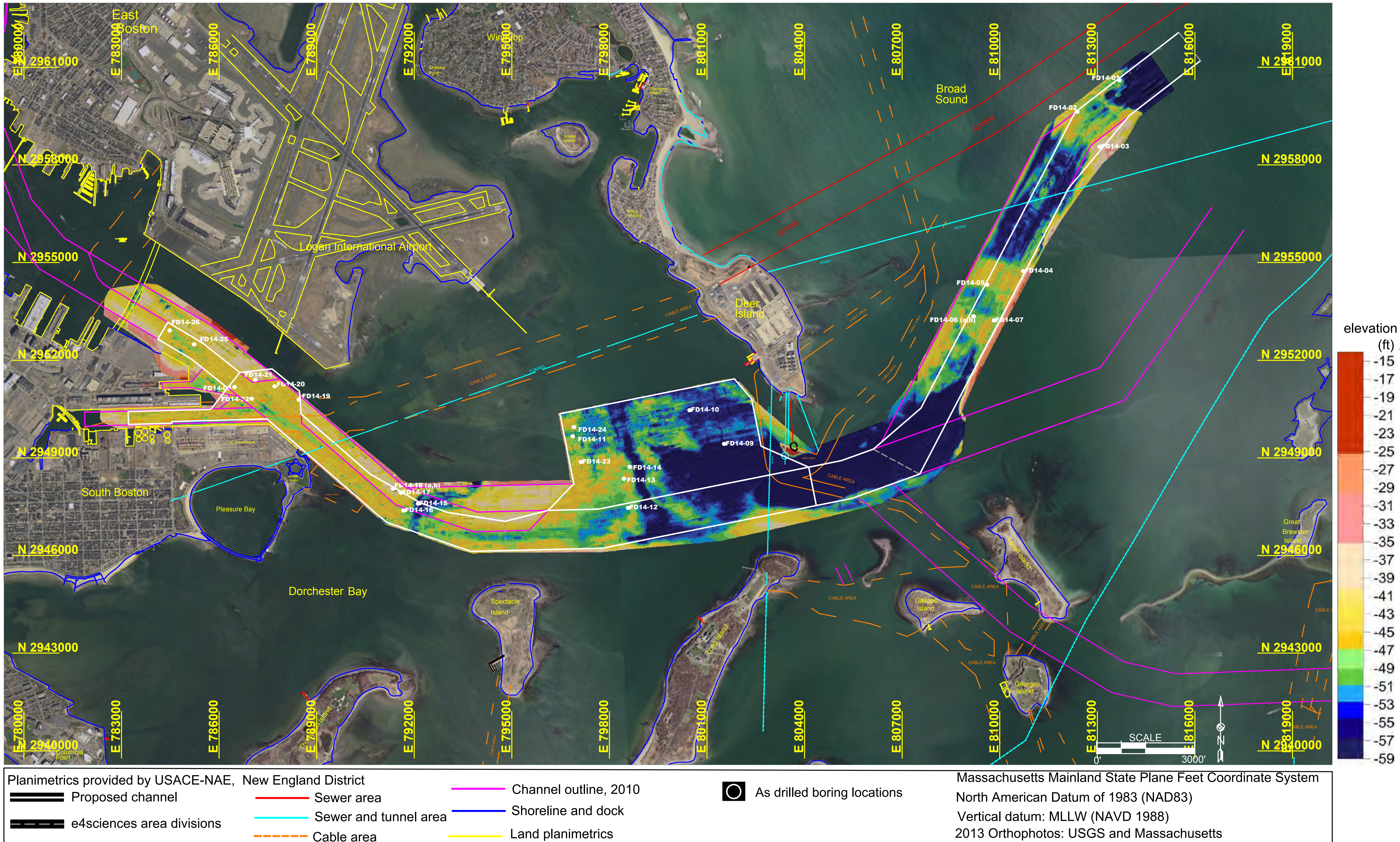


Figure 23. Top of Pleistocene sediments.

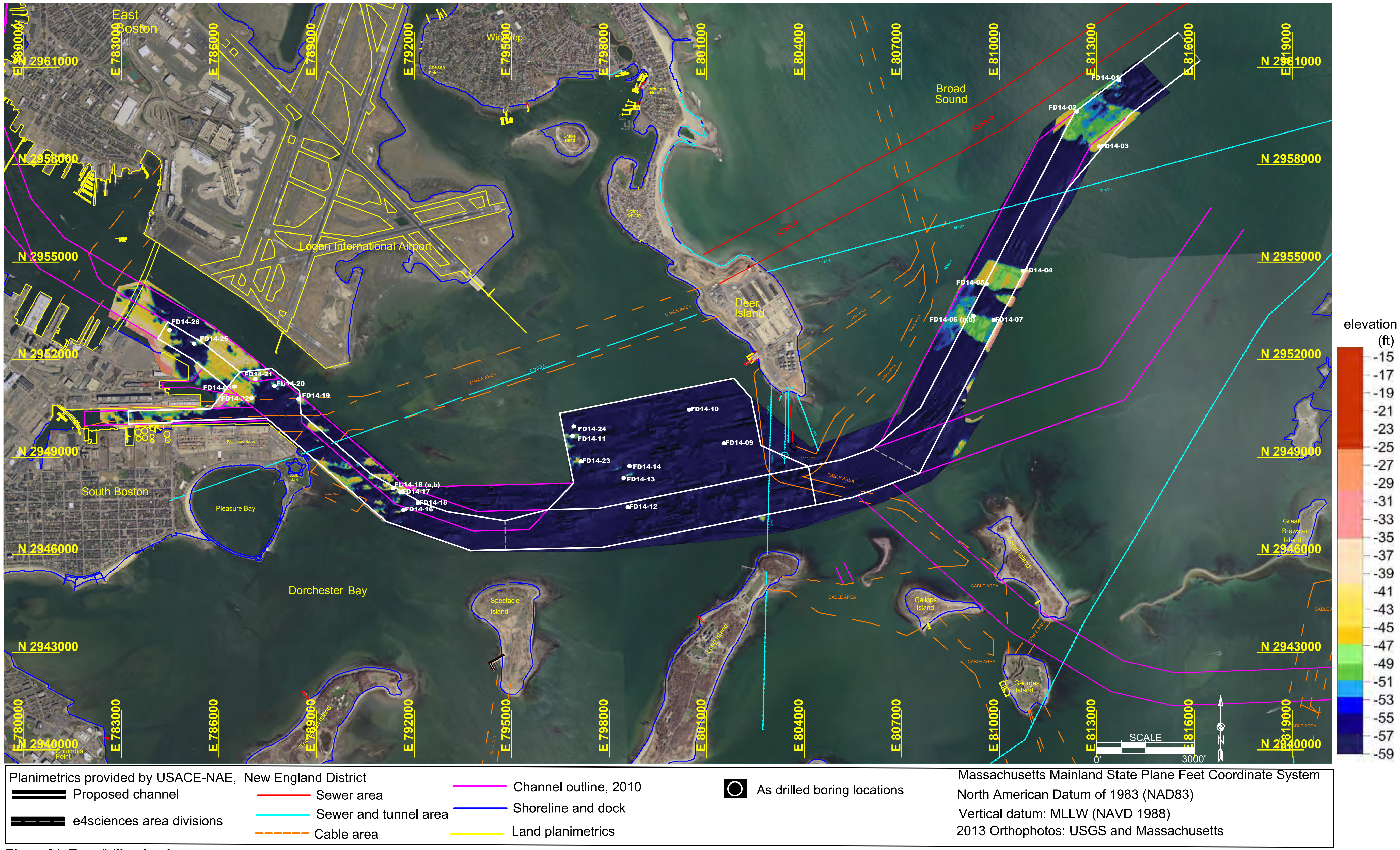
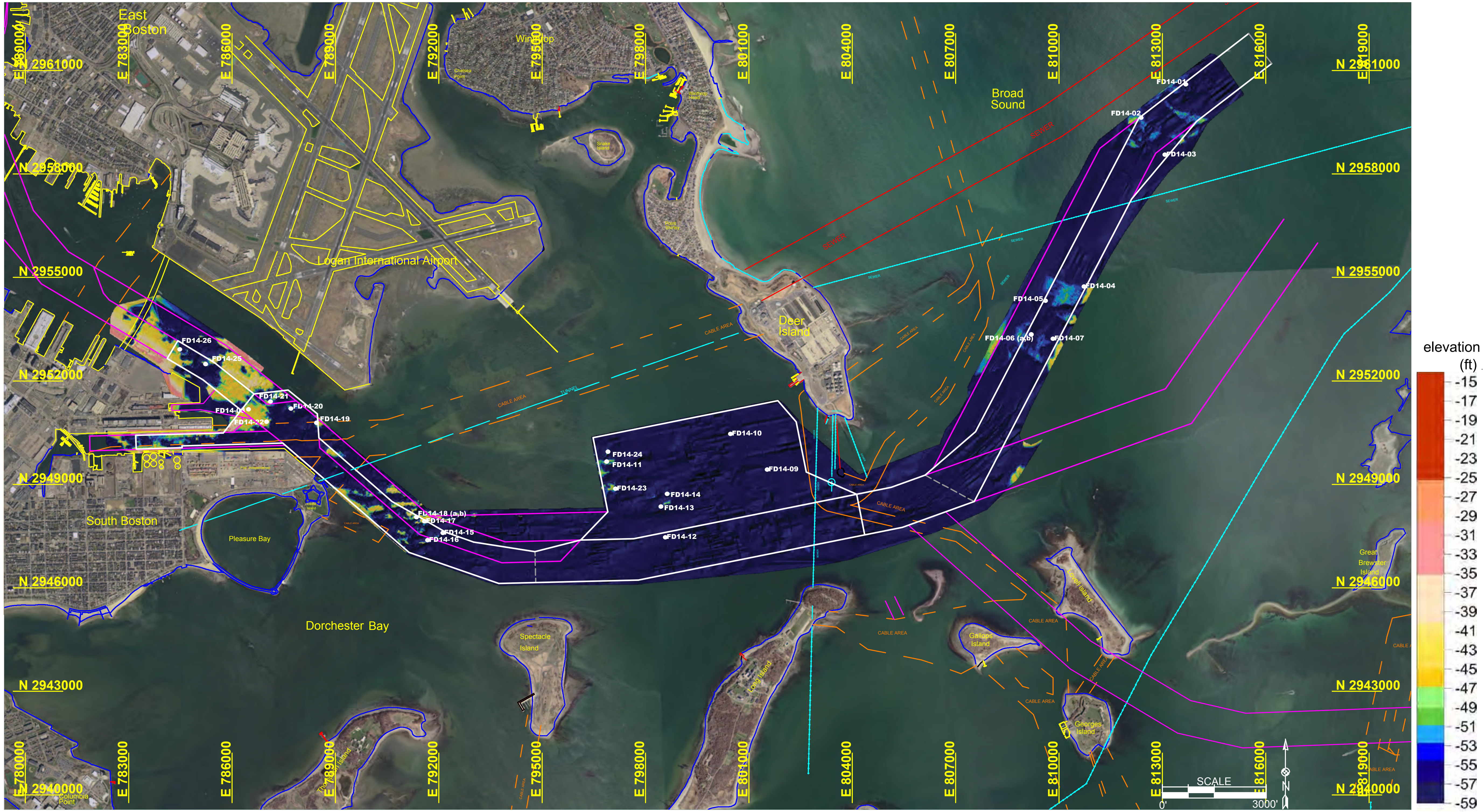


Figure 24. Top of till and rock.



Planimetrics provided by USACE-NAE, New England District

- Proposed channel
- e4sciences area divisions
- Sewer area
- Sewer and tunnel area
- Cable area
- Channel outline, 2010
- Shoreline and dock
- Land planimetrics
- As drilled boring locations

Massachusetts Mainland State Plane Feet Coordinate System
North American Datum of 1983 (NAD83)
Vertical datum: MLLW (NAVD 1988)
2013 Orthophotos: USGS and Massachusetts

Figure 25. Top of rock.

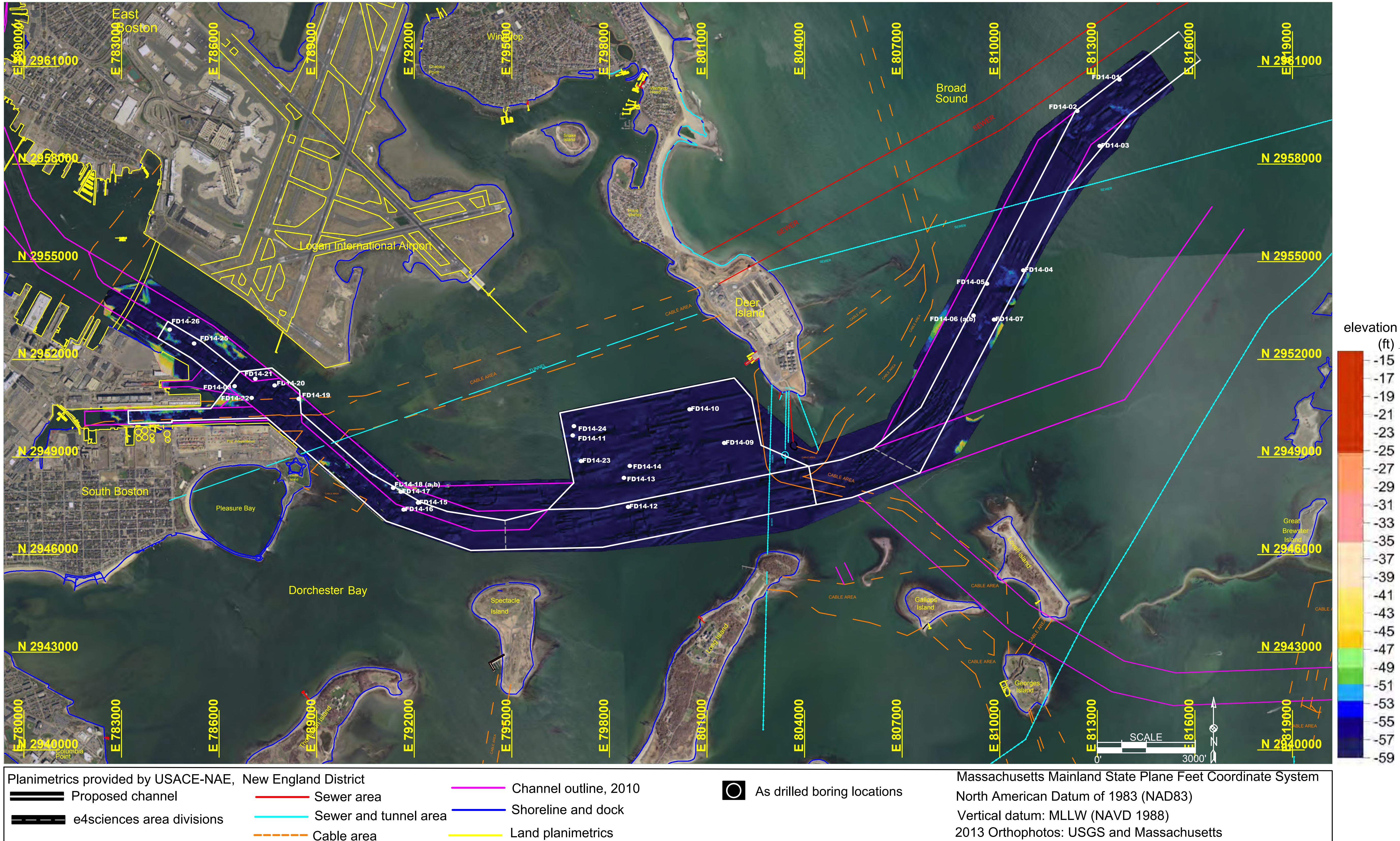


Figure 26. Top of fast rock.

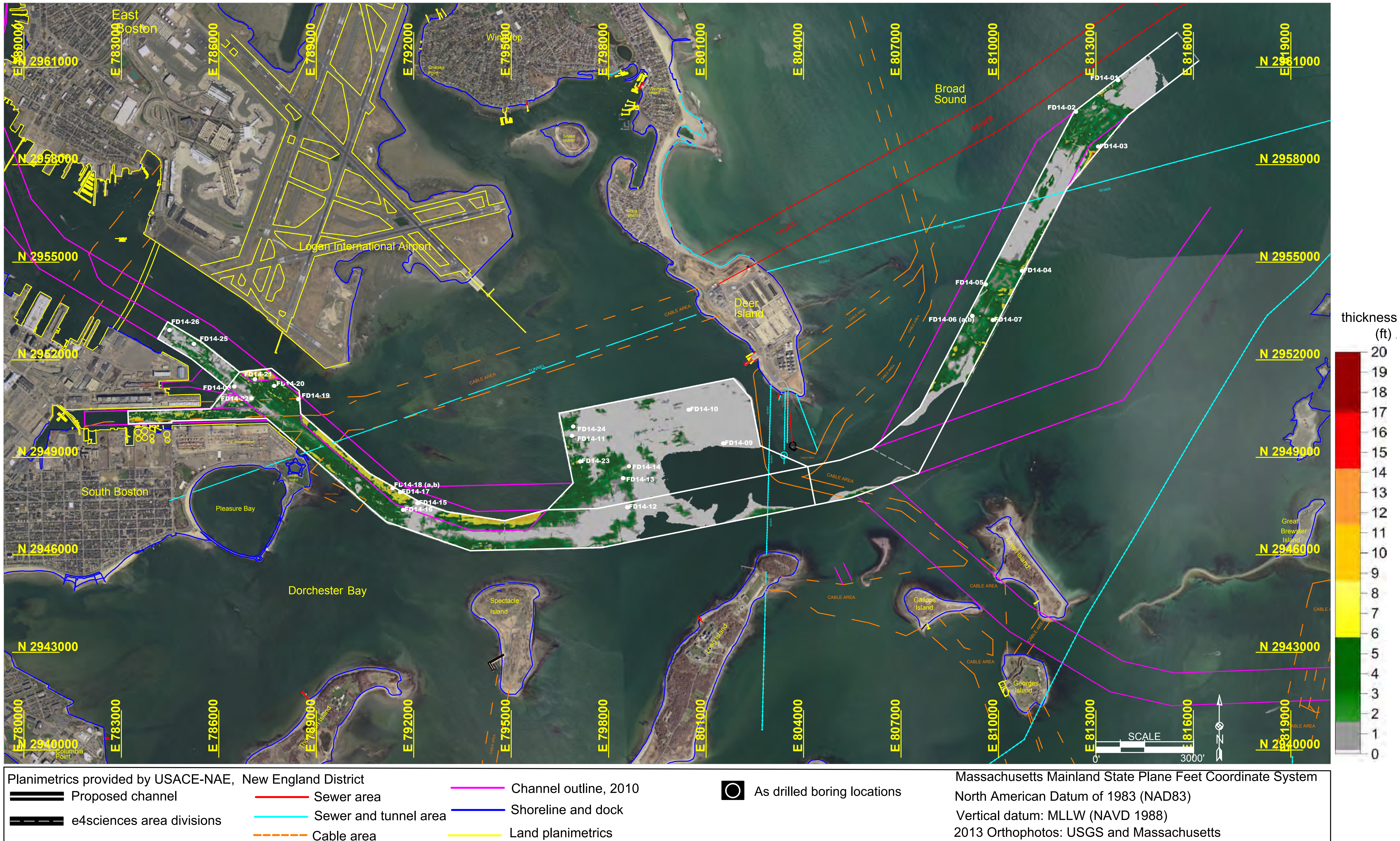


Figure 27. Isopach map of Pleistocene sediments.

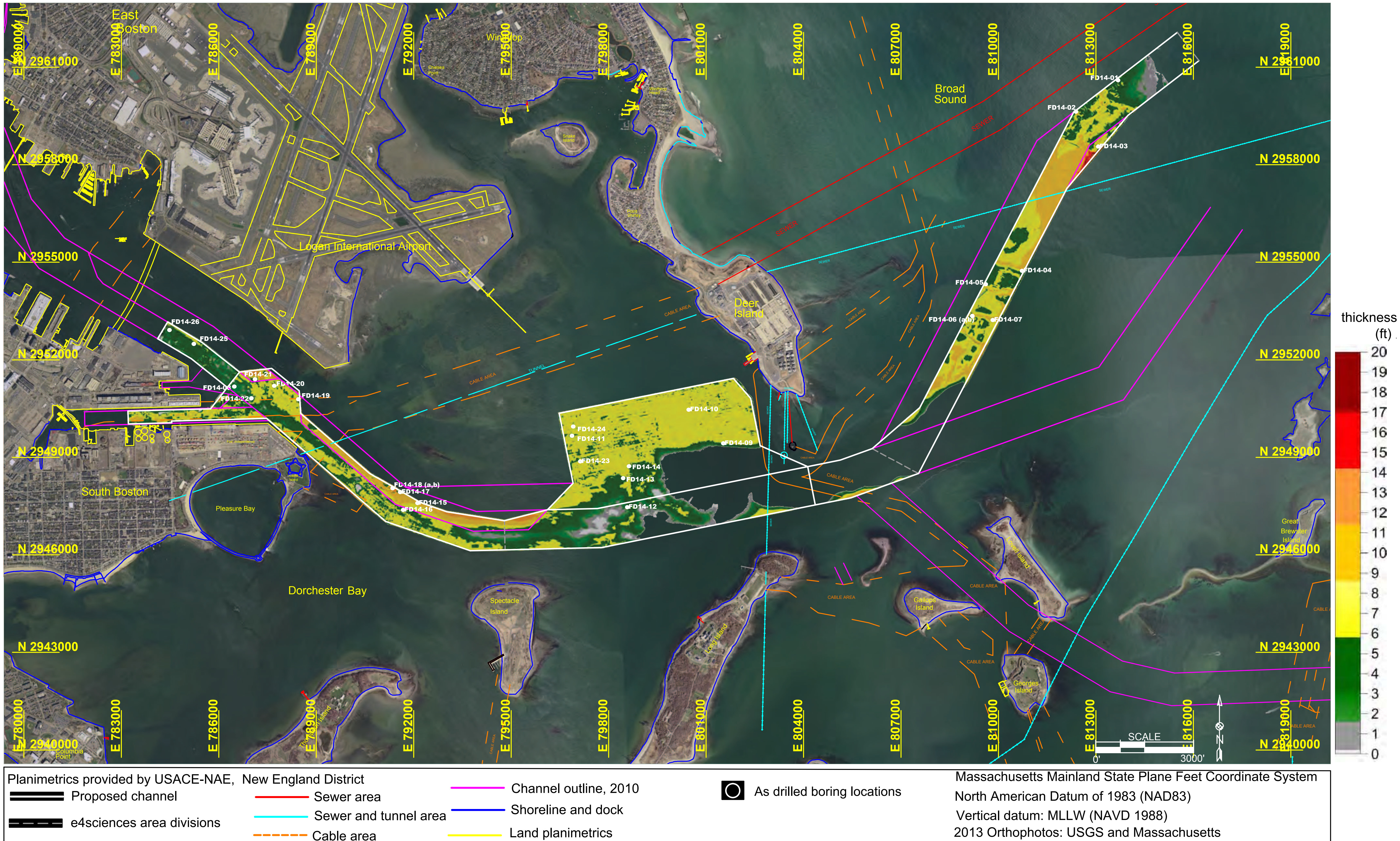


Figure 28. Isopach map of Holocene and Pleistocene sediment.

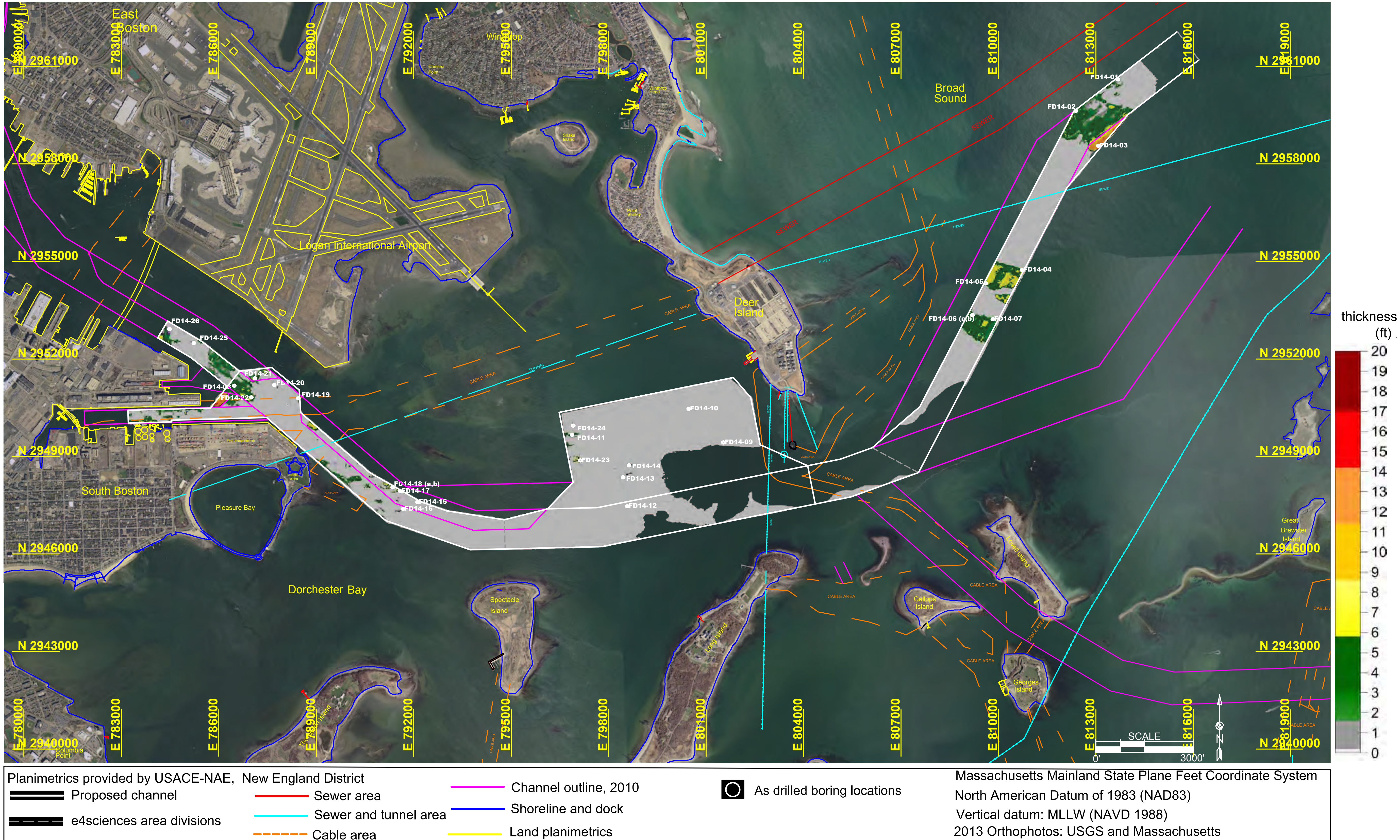
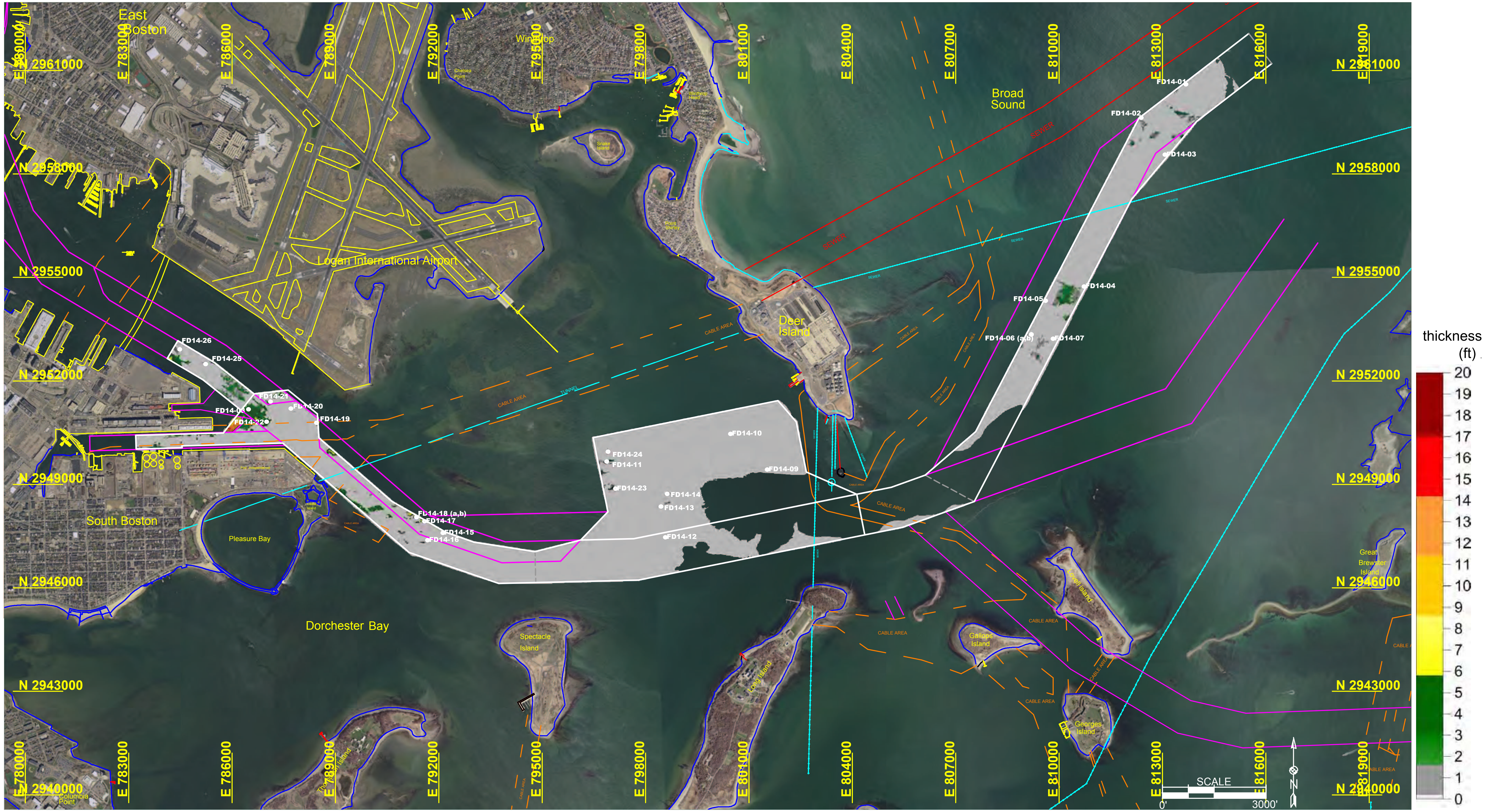


Figure 29. Isopach map of till and rock.



Planimetrics provided by USACE-NAE, New England District

Proposed channel

e4sciences area divisions

Sewer area

Sewer and tunnel area

Cable area

Channel outline, 2010

Shoreline and dock

Land planimetrics

As drilled boring locations

Massachusetts Mainland State Plane Feet Coordinate System

North American Datum of 1983 (NAD83)

Vertical datum: MLLW (NAVD 1988)

2013 Orthophotos: USGS and Massachusetts

Figure 30. Isopach map of rock.

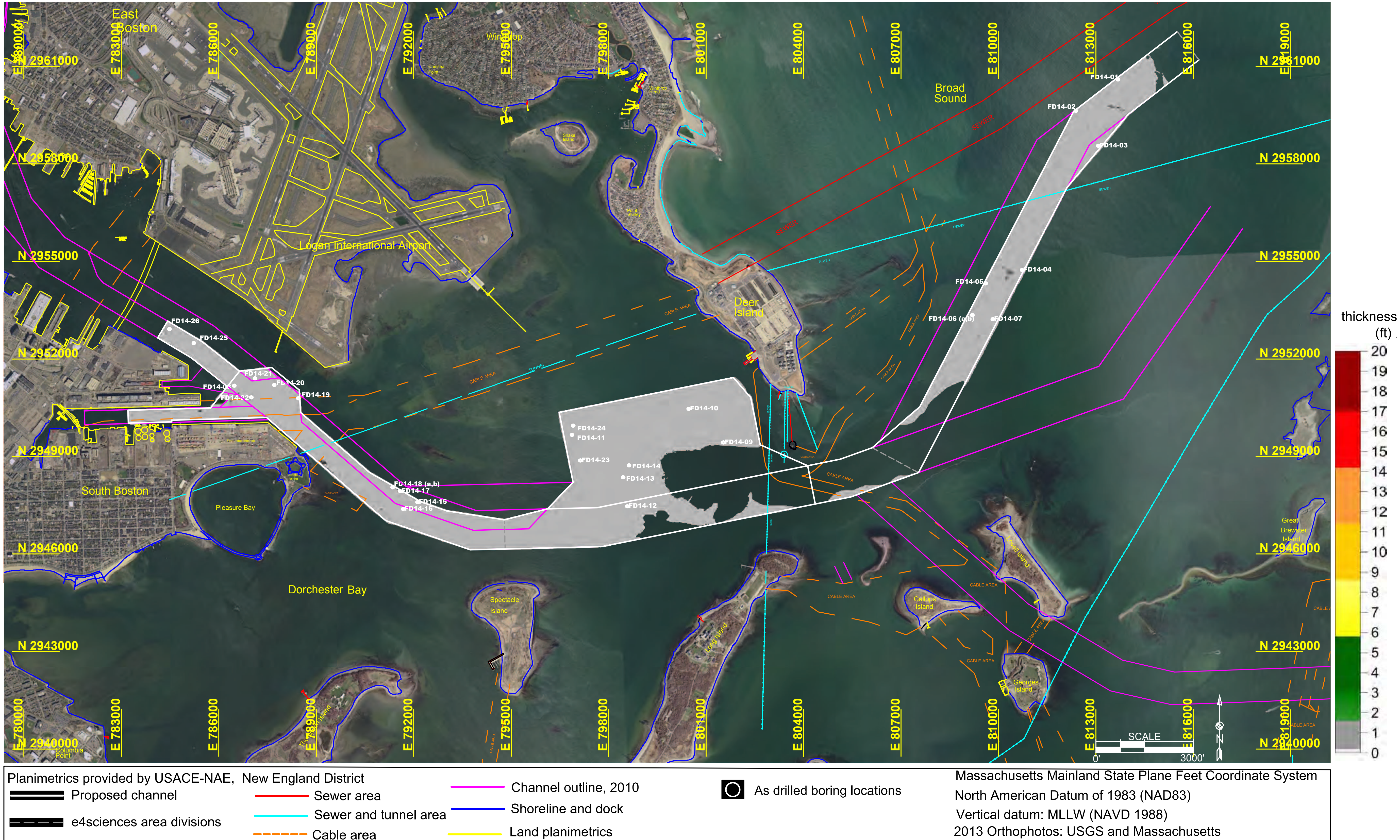


Figure 31. Isopach of fast rock.

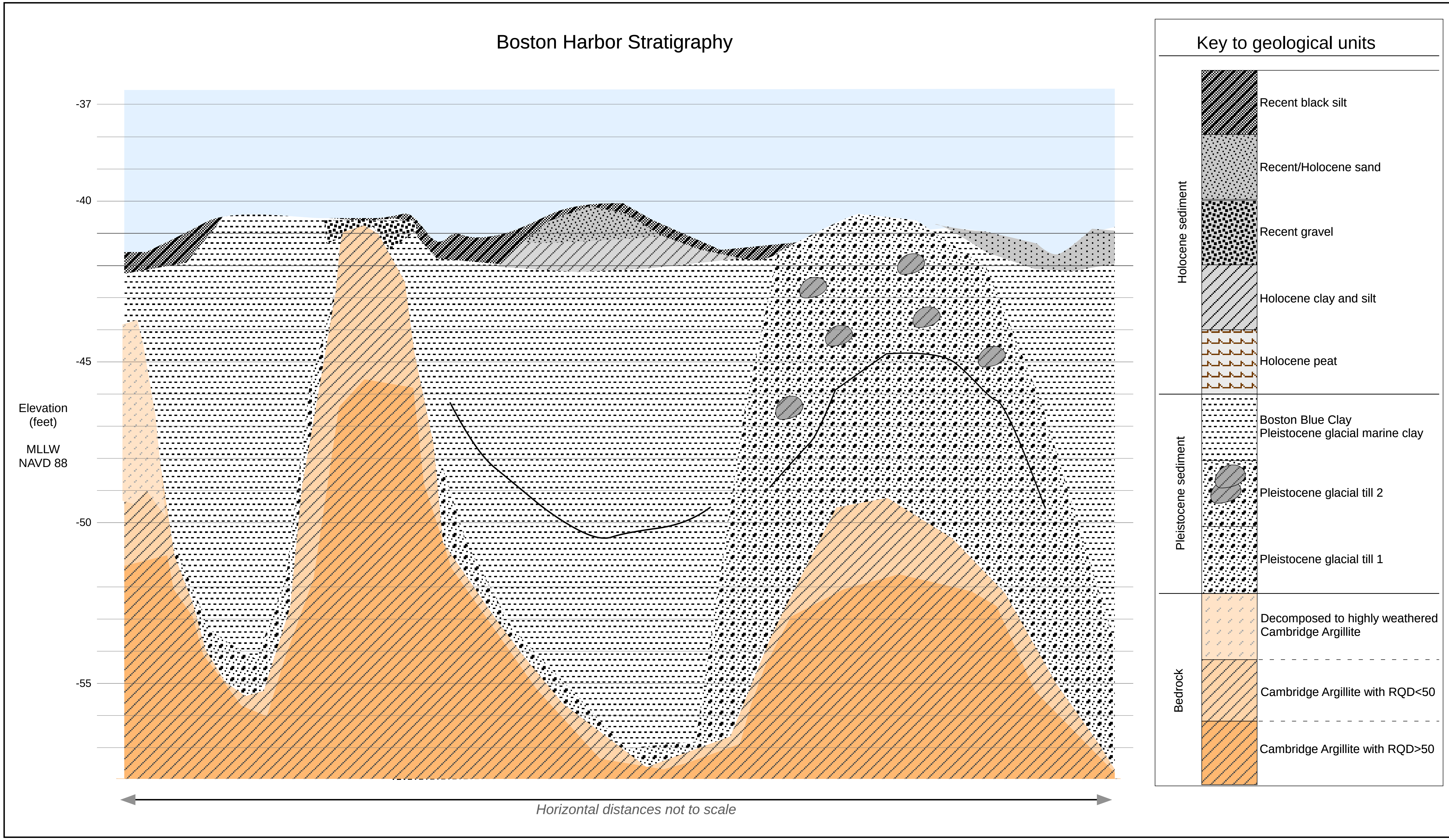


Figure 32. Schematic stratigraphy of entire Harbor Deepening Project.

4.1 Analysis of exploration

4.1.1 Areas

Table 13 summarizes the three different project areas in the harbor-deepening project. Roughly 30% the contract areas are already below grade, principally in the North Channel and Main Ship Channel near Deer Island. Table 13 lists the areas where sediments and rock above grade. Table 13a includes the area to rock and hard material above grade.

Table 13. Estimates of area above the newly authorized grade.

Project	Location	Total area	Fraction of total area	Area above grade	Fraction above grade	Area in side slopes
		sqft	per total	sqft	per project	sqft
-51ft	North Channel, MSCPRA	19,400,970	0.2921	11,524,360	0.5940	752,731
-47ft	MSC, PRA, RC, TB	45,424,659	0.6839	30,095,759	0.6625	1,214,979
-45ft	MSCMMT	1,595,743	0.0240	1,562,239	0.9790	85,448
	Total	66,421,372	1.0000	43,182,359	0.6501	2,053,158

Table 13a. Estimates of area of rock and hard bottom above grade.

Project	Location	Area above grade	Area of rock above grade	Fraction of rock above elevation
		sqft	sqft	per project
-51ft	North Channel, MSCPRA	11,524,360	256,700	0.0223
-47ft	MSC, PRA, RC, TB	30,095,759	835,722	0.0278
-45ft	MSCMMT	1,562,239	181,738	0.1163
	Total	43,182,359	1,274,161	0.0295

The rock constitutes 2.95% of the total area above grade.

Table 14 lists the estimates of rock area in the required overdepth in case of rock and hard bottom. The rock constitutes about 5.9% of the total area when we include the required overdepth.

Table 14. Estimates of area of rock above the required 2ft overdepth.

Project	Location	First paid overdepth	Area above overdepth	Area of rock above overdepth	Fraction of rock above elevation
			sqft	sqft	per project
-51ft	North Channel, MSCPRA	-53ft	12,394,199	948,307	0.0765
-47ft	MSC, PRA, RC, TB	-49ft	32,670,376	1,241,491	0.0380
-45ft	MSCMMT	-47ft	1,586,210	548,683	0.3459
	Total		46,650,785	2,738,481	0.0587

4.1.2 Volumes

Table 15 summarizes the volume estimates. Table 15 does not add the allowed overdepth in the case of rock. The total volume of material is 8.01 million cuyd. Rock is defined as bedrock material that is in place regardless of condition. Note that the area where the rock reaches the surface constitutes a small fraction in the North and MSCPRA Channels. The volume of the rock is roughly 2.2% of the total volume in all of the projects. In the MSCMMT, the rock volume exceeds 12% of the volume.

Table 15. Estimates of total volumes above the newly authorized grade.

Grade	Location	Volume above grade	Volume of side slope to grade	Sum of volumes above grade	Fraction above elevation	Rock volume above elevation	Fraction of rock above elevation
		cuyd	cuyd	cuyd	per total	cuyd	per project
-51ft	North Channel, MSCPRA	2,733,925	137,714	2,871,638	0.3584	6,566	0.0023
-47ft	MSC, PRA, RC, TB	4,771,536	208,502	4,980,038	0.6216	85,849	0.0172
-45ft	MSCMMT	150,740	9,523	160,263	0.0200	7,197	0.0449
	Total	7,656,200	355,739	8,011,939	1.0000	99,611	0.0124

Table 16 and 16a list the volumes for the optional 2ft overdepth in sediments or in the case of rock, the required 2ft overdepth.

Table 16. Estimates of total volume above optional overdepth or required 2ft overdepth in the case of rock or hard bottom.

First 2ft overdepth	Location	Sum of volumes above grade	Interval volume from grade to first overdepth	Interval volume of side slope from grade to OD1	Sum of volumes above first overdepth	Fraction above elevation
		cuyd	cuyd	cuyd	cuyd	per total
-53ft	North Channel, MSCPRA	2,871,638	890,615	30,371	3,792,625	0.3288
-49ft	MSC, PRA, RC, TB	4,980,038	2,339,802	129,701	7,449,541	0.6459
-47ft	MSCMMT	160,263	117,718	13,069	291,050	0.0252
	Total	8,011,939	3,348,135	173,142	11,533,216	1.0000

Table 16a. Estimates of volume above optional 2ft overdepth or required 2ft overdepth in the case of rock or hard bottom.

First 2ft overdepth	Location	Sum of volumes above first overdepth	Interval rock volume grade to first overdepth	Cumulative rock volume above first overdepth	Fraction of rock above elevation
		cuyd	cuyd	cuyd	per project
-53ft	North Channel, MSCPRA	3,792,625	43,163	49,729	0.0131
-49ft	MSC, PRA, RC, TB	7,449,541	78,210	164,058	0.0220
-47ft	MSCMMT	291,050	27,467	34,663	0.1191
	Total	11,533,216	148,840	248,451	0.0215

Table 16b. Estimates of volume above second optional 2ft overdepth in the case of rock or hard bottom.

Second 2ft overdepth	Location	Sum of all volumes above first overdepth	Interval volume from first to second overdepth	Sum of all volumes above second overdepth	Fraction above elevation	Interval rock volume from first to second overdepth	Cumulative rock volume above second overdepth	Fraction of rock above elevation
		cuyd	cuyd	cuyd	per total	cuyd	cuyd	per project
-55ft	North Channel, MSCPRA	3,792,625	274,012	4,066,637	0.3382	94,076	143,805	0.0354
-51ft	MSC, PRA, RC, TB	7,449,541	159,878	7,609,419	0.6329	106,254	270,313	0.0355
-49ft	MSCMMT	291,050	56,204	347,254	0.0289	46,878	81,541	0.2348
	Total	11,533,216	490,094	12,023,310	1.0000	247,208	495,659	0.0412

Above grade, the condition of the rock varies from decomposed to weathered to fractured to intact. Table 17 lists the volume and proportion of fast rock relative to the total volume of rock above grade. The fast rock may resistant to ripping. In the MSCRCA, most of the rock is fast rock.

Table 17. Estimates of rock volume above the newly authorized grade.

Grade	Location	Rock volume above grade	Fraction of rock above grade	Volume of fast rock above grade	Fraction of fast rock per rock
		cuyd	per project	cuyd	per project
-51ft	North Channel, MSCPRA	6,566	0.0023	12	0.0019
-47ft	MSC, PRA, RC, TB	85,849	0.0172	2,932	0.0342
-45ft	MSCMMT	7,197	0.0449	0	0.0000
	Total	99,611	0.0124	2,944	0.0296

4.2 Sums of each of the materials per reach

The maps in section 4.1 allow us to determine each of the materials, the silt, the Holocene and Pleistocene sediments, till and rock, rock, and fast rock per reach.

Table 18 lists the total area, and area above the newly authorized grade per reach. The fractions are calculated per total area per reach.

Table 18. Estimates of area of Holocene and Pleistocene sediment above the newly authorized grade. The fractions are per total area for all area of project segments.

	Grade	Total area	Area above grade	Area side slope	Total area above grade including side slopes	Fraction of total area in the project segments
Reach	ft, MLLW	sqft	sqft	sqft	sqft	
North Channel	-51	16,220,140	11,225,358	722,691	11,948,049	0.6921
MSCPRA -51ft	-51	3,180,820	299,003	30,039	329,042	0.0940
MSCPRA -47ft	-47	15,136,620	4,664,000	126,136	4,790,136	0.3081
PRA	-47	19,059,960	14,604,841	350,215	14,955,056	0.7663
MSCRCA	-47	8,093,960	7,795,707	542,795	8,338,502	0.9632
Reserved Channel	-47	1,896,650	1,865,172	154,271	2,019,442	0.9834
Turning Basin	-47	1,237,470	1,166,040	41,563	1,207,603	0.9423
MSCMMT	-45	1,595,743	1,562,239	85,448	1,647,687	0.9790
Total		66,421,363	43,182,359	2,053,158	45,235,516	0.6501

Table 19 lists the area and volume of Holocene and Pleistocene sediment above the newly authorized grade per reach. The fractions are per reach per total volume for all reaches.

Table 19. Estimates of volume for Holocene and Pleistocene sediments in the channels above the newly authorized grade. The fractions are per reach per total of sediment volume for all reaches.

	Grade	Volume of sediment above grade	Volume of side slope above grade	Cumulative volume of sediment above grade	Fraction of total sediment volume
Reach	ft, MLLW	cuyd	cuyd	cuyd	
North Channel	-51	2,308,489	134,541	2,443,030	0.3234
MSCPRA -51ft	-51	47,672	3,173	50,845	0.0067
MSCPRA -47ft	-47	473,224	15,572	488,797	0.0663
PRA	-47	2,384,030	39,056	2,423,086	0.3340
MSCRCA	-47	1,262,133	123,763	1,385,896	0.1768
Reserved Channel	-47	298,610	22,928	321,538	0.0418
Turning Basin	-47	229,971	7,183	237,154	0.0322
MSCMMT	-45	133,918	9,523	143,442	0.0188
Total		7,138,048	355,739	7,493,786	1.0000

Table 20 lists the estimates of area (Table 20) and volume (Table 20a) for the Holocene and Pleistocene sediments above the optional 2ft overdepth or in the case of rock or hard bottom, the required 2ft overdepth.

Table 20. Estimates of Holocene and Pleistocene sediment area above the optional 2ft overdepth.

	Optional 2ft overdepth	Sediment area above first overdepth	Side slope area above first overdepth	Total area of sediment above first overdepth	Fraction of the total area
Reach	ft, MLLW	sqft	sqft	sqft	
North Channel	-53	12,019,687	735,177	12,754,864	0.1920
MSCPRA -51ft	-53	374,512	42,354	416,866	0.0063
MSCPRA -47ft	-49	6,578,865	194,276	6,773,141	0.1020
PRA	-49	15,002,555	403,791	15,406,346	0.2319
MSCRCA	-49	8,045,075	607,394	8,652,469	0.1303
Reserved Channel	-49	1,877,841	176,552	2,054,393	0.0309
Turning Basin	-49	1,166,040	47,466	1,213,506	0.0183
MSCMMT	-47	1,586,210	109,838	1,696,047	0.0255
Total		46,650,785	2,316,847	48,967,632	0.7372

Table 20a. Estimates of Holocene and Pleistocene sediment volume above optional 2ft overdepth.

	Optional 2ft overdepth	Interval sediment volume from grade to overdepth 1	Interval volume of side slope from grade to first overdepth	Cumulative sediment volume to overdepth 1	Fraction of total sediment volume
Reach	ft, MLLW	cuyd	cuyd	cuyd	
North Channel	-53	614,450	27,122	3,084,601	0.2905
MSCPRA -51ft	-53	25,488	3,250	79,583	0.0075
MSCPRA -47ft	-49	419,513	17,292	925,602	0.0872
PRA	-49	1,098,185	33,685	3,554,956	0.3348
MSCRCA	-49	535,135	61,288	1,982,319	0.1867
Reserved Channel	-49	100,744	10,882	433,164	0.0408
Turning Basin	-49	79,065	6,553	322,772	0.0304
MSCMMT	-47	78,490	13,069	235,001	0.0221
Total		2,951,070	173,142	10,617,999	1.0000

In the optional overdepth in case of the rock or hard bottom, some sediments, a small amount, are involved as wedges off the rock.

Table 21. Estimates of area and volume of the Holocene and Pleistocene sediments above the optional overdepth in the case of hard bottom. The fractions are per reach per total of till and rock volume for all reaches.

	Second overdepth	Sediment area above second overdepth in the case of hard bottom	Interval sediment volume from first to first overdepth	Cumulative sediment volume to second overdepth	Fraction of total sediment volume
Reach	ft, MLLW	sqft	cuyd	cuyd	
North Channel	-55	12,040,583	3,993	3,088,595	0.2903
MSCPRA -51ft	-55	374,513	0	79,583	0.0075
MSCPRA -47ft	-51	6,872,670	71	925,674	0.0870
PRA	-51	15,059,374	2,466	3,557,421	0.3343
MSCRCA	-51	8,046,909	6,383	1,988,702	0.1869
Reserved Channel	-51	1,877,841	5,071	438,236	0.0412
Turning Basin	-51	1,166,040	2,097	324,868	0.0305
MSCMMT	-49	1,586,210	3,032	238,033	0.0224
Total		47,024,138	23,114	10,641,113	1.0000

Table 22 lists the area and volume of till and rock per reach. The fractions are calculated per reach per total volume of till and rock for all reaches.

Table 22. Estimates of area and volume above the newly authorized grade for till and rock in the channels. The fractions are per reach per total of till and rock volume for all reaches.

	Grade	Area of till/rock above grade	Volume of till/rock above grade	Fraction of total till/rock volume
Reach	ft, MLLW	sqft	cuyd	
North Channel	-51	3,117,204	377,763	0.7291
MSCPRA -51ft	-51	0	0	0.0000
MSCPRA -47ft	-47	45	2	0.0000
PRA	-47	15,479	703	0.0014
MSCRCA	-47	647,304	59,450	0.1147
Reserved Channel	-47	417,784	57,736	0.1114
Turning Basin	-47	80,721	5,677	0.0110
MSCMMT	-45	366,214	16,821	0.0325
Total		4,644,751	518,152	1.0000

Table 22a estimates the area and volume of the till and rock above the required overdepth.

Table 22a. Estimates of area and volume above the required 2ft overdepth for till and rock in the channels. The fractions are per reach per total of till and rock volume for all reaches.

	Required 2ft overdepth	Area of till/rock above first overdepth	Interval volume of till/rock from grade to first overdepth	Cumulative volume of till/rock to first overdepth	Fraction of total till/rock volume
Reach	ft, MLLW	sqft	cuyd	cuyd	
North Channel	-53	3,537,976	250,677	628,441	0.6867
MSCPRA -51ft	-53	0	0	0	0.0000
MSCPRA -47ft	-49	387	8	10	0.0000
PRA	-49	61,754	2,666	3,368	0.0037
MSCRCA	-49	882,118	57,500	116,950	0.1278
Reserved Channel	-49	608,349	39,146	96,882	0.1059
Turning Basin	-49	131,088	7,840	13,518	0.0148
MSCMMT	-47	648,420	39,228	56,049	0.0612
Total		5,870,093	397,065	915,217	1.0000

Table 22b estimates the area and volume of the till and rock above the optional 2ft overdepth in case of rock or hard bottom.

Table 22b. Estimates of area and volume above the required 2ft overdepth for till and rock in the channels. The fractions are per reach per total of till and rock volume for all reaches.

	Second overdepth	Area of till/rock above second overdepth	Interval volume of till/rock from first to second overdepth	Cumulative volume of till/rock to second overdepth	Fraction of total till/rock volume
Reach	ft, MLLW	sqft	cuyd	cuyd	
North Channel	-55	3,699,164	270,019	898,459	0.6500
MSCPRA -51ft	-55	0	0	0	0.0000
MSCPRA -47ft	-51	2,196	91	102	0.0001
PRA	-51	127,024	6,944	10,312	0.0075
MSCRCA	-51	1,071,518	72,988	189,938	0.1374
Reserved Channel	-51	767,554	51,784	148,666	0.1076
Turning Basin	-51	190,057	11,982	25,499	0.0184
MSCMMT	-49	758,756	53,172	109,221	0.0790
Total		6,616,270	466,980	1,382,198	1.0000

Table 23 lists the area and volume of rock above the newly authorized grade in the channels per channel section. The fractions are calculated per volume of rock per reach for all reaches and the total volume of all materials per reach.

Table 23. Estimates of area and volume above the newly authorized grade for rock. The fractions are per reach per total of rock for all reaches and total volume of material per reach.

	Grade	Area of rock above grade	Volume of rock above grade	Fraction of total rock volume	Fraction of total volume
Reach	ft, MLLW	sqft	cuyd		
North Channel	-51	256,700	6,566	0.0659	0.0023
MSCPRA -51ft	-51	0	0	0.0000	0.0000
MSCPRA -47ft	-47	0	0	0.0000	0.0000
PRA	-47	6,677	210	0.0021	0.0001
MSCRCA	-47	511,550	40,258	0.4041	0.0279
Reserved Channel	-47	293,308	43,971	0.4414	0.1159
Turning Basin	-47	24,187	1,410	0.0142	0.0058
MSCMMT	-45	181,738	7,197	0.0722	0.0449
Total		1,274,161	99,611	1.0000	0.0124

Table 23a lists the estimate for rock above the 2ft required overdepth.

Table 23a. Estimates of area and volume of rock above the 2ft required overdepth in the case of hard bottom. The fractions are per reach per total of rock for all reaches and total volume of material per reach.

	First overdepth	Area of rock above first overdepth	Interval volume of rock from grade to first overdepth	Cumulative volume of rock to first overdepth	Fraction of total rock volume	Fraction of total volume
Reach	ft, MLLW	sqft	cuyd	cuyd		
North Channel	-53	948,307	43,163	49,729	0.2002	0.0134
MSCPRA -51ft	-53	0	0	0	0.0000	0.0000
MSCPRA -47ft	-49	3	0	0	0.0000	0.0000
PRA	-49	41,264	1,588	1,799	0.0072	0.0005
MSCRCA	-49	705,810	45,664	85,922	0.3458	0.0409
Reserved Channel	-49	444,622	28,241	72,212	0.2906	0.1362
Turning Basin	-49	49,791	2,716	4,126	0.0166	0.0123
MSCMMT	-47	548,683	27,467	34,663	0.1395	0.1191
Total		2,738,481	148,840	248,451	1.0000	0.0215

Table 23b lists the estimate for rock above the optional 2ft overdepth below the hard bottom.

Table 23b. Estimates of area and volume of rock above the optional 2ft overdepth in the case of hard bottom. The fractions are per reach per total of rock for all reaches and total volume of material per reach.

	Second overdepth	Area of rock above second overdepth	Interval volume of rock from first to second overdepth	Cumulative volume of rock to second overdepth	Fraction of total rock volume	Fraction of total volume
Reach	ft, MLLW	sqft	cuyd	cuyd		
North Channel	-55	1,500,928	94,076	143,805	0.5788	0.0361
MSCPRA -51ft	-55	0	0	0	0.0000	0.0000
MSCPRA -47ft	-51	8	0	1	0.0000	0.0000
PRA	-51	93,711	4,982	6,780	0.0273	0.0019
MSCRCA	-51	878,440	59,135	145,057	0.5838	0.0666
Reserved Channel	-51	551,311	37,349	109,561	0.4410	0.1867
Turning Basin	-51	79,773	4,788	8,914	0.0359	0.0254
MSCMMT	-49	687,924	46,878	81,541	0.3282	0.2348
Total		3,792,096	247,208	495,659	1.9950	0.0412

Table 24 lists the area and volume of fast rock above the newly authorized grade. Fast rock is defined as rock whose seismic compressional wave velocity is greater than 2,700m/s. The fractions are per reach per volume of fast rock and per reach per total material.

Table 24. Estimates of area and volume for fast rock above the newly authorized grade. The fractions are per reach per volume of fast rock per total rock volume and per volume of total volume of material per reach.

	Newly authorized grade	Area of fast rock above grade	Volume of fast rock above grade	Fraction of total rock volume	Fraction of total volume
Reach	ft, MLLW	sqft	cuyd		
North Channel	-51	801	12	0.0019	0.0000
MSCPRA -51ft	-51	0	0	0.0000	0.0000
MSCPRA -47ft	-47	0	0	0.4462	0.0000
PRA	-47	0	0	0.0000	0.0000
MSCRCA	-47	23,744	1,615	0.0401	0.0011
Reserved Channel	-47	35,399	1,317	0.0299	0.0035
Turning Basin	-47	5	0	0.0000	0.0000
MSCMMT	-45	0	0	0.0000	0.0000
Total		59,949	2,944	0.0296	0.0004

Table 24a lists the area and volume of fast rock above the 2ft required overdepth in the case of rock or hard bottom. The fractions are per reach per volume of fast rock and per reach per total material.

Table 24a. Estimates of area and volume for fast rock above the required 2ft overdepth. The fractions are per reach per volume of fast rock per total rock volume and per volume of total volume of material per reach.

	Required 2ft overdepth	Area of fast rock above first overdepth	Interval volume of fast rock from grade to first overdepth	Cumulative volume of fast rock to first overdepth	Fraction of total rock volume	Fraction of total volume
Reach	ft, MLLW	Sqft	cuyd	cuyd		
North Channel	-53	51,018	978	990	0.0199	0.0003
MSCPRA -51ft	-53	0	0	0	0.0000	0.0000
MSCPRA -47ft	-49	2	0	0	0.0000	0.0000
PRA	-49	1	0	0	0.0000	0.0000
MSCRCA	-49	45,501	2,479	4,094	0.0477	0.0012
Reserved Channel	-49	103,029	4,733	6,050	0.0838	0.0089
Turning Basin	-49	1,071	28	28	0.0069	0.0001
MSCMMT	-47	78	0	0	0.0000	0.0000
Total		200,700	8,218	11,163	0.0449	0.0007

Table 24b lists the area and volume of fast rock above the optional 2ft overdepth in the case of rock or hard bottom. The fractions are per reach per volume of fast rock and per reach per total material.

Table 24b. Estimates of area and volume for fast rock above the optional 2ft overdepth. The fractions are per reach per volume of fast rock per total rock volume and per volume of total volume of material per reach.

Reach	Optional 2ft overdepth ft, MLLW	Area of fast rock above second overdepth sqft	Interval volume of fast rock from first to second overdepth cuyd	Cumulative volume of fast rock to second overdepth cuyd	Fraction of total rock volume	Fraction of total volume
North Channel	-55	503,585	17,477	18,467	0.1284	0.0046
MSCPRA -51ft	-55	0	0	0	0.0000	0.0000
MSCPRA -47ft	-51	8	0	0	0.0000	0.0000
PRA	-51	400	5	5	0.0008	0.0000
MSCRCA	-51	84,816	4,679	8,773	0.0605	0.0040
Reserved Channel	-51	228,780	12,437	18,487	0.1687	0.0315
Turning Basin	-51	3,456	162	191	0.0214	0.0005
MSCMMT	-49	5,905	168	169	0.0021	0.0005
Total		826,949	34,928	46,092	0.0930	0.0038

Table 25 lists the area and volume of all material above the newly authorized grade. This includes side slope volumes. The fractions are per reach per total volume for all reaches.

Table 25. Estimates of area and volume for all material above the newly authorized grade including side slopes. The fractions are per reach per total volume for all reaches.

Reach	Newly authorized grade ft, MLLW	Area above grade sqft	Volume above grade cuyd	Fraction of total volume
North Channel	-51	11,948,049	2,820,793	0.3521
MSCPRA -51ft	-51	329,042	50,845	0.0063
MSCPRA -47ft	-47	4,790,136	488,799	0.0610
PRA	-47	14,955,056	2,423,788	0.3025
MSCRCA	-47	8,338,502	1,445,346	0.1804
Reserved Channel	-47	2,019,442	379,274	0.0473
Turning Basin	-47	1,207,603	242,831	0.0303
MSCMMT	-45	1,647,687	160,263	0.0200
Total		45,235,516	8,011,939	1.0000

Table 25a lists the volume of all material above the first 2ft overdepth per reach. The fractions were calculated per reach for all materials for all reaches.

Table 25a. Estimates of all areas and volumes above the first overdepth include side slopes. The fractions are per reach.

Reach	First 2ft overdepth ft, MLLW	Area above first overdepth sqft	Volume above first overdepth cuyd	Fraction of total volume
North Channel	-53	12,754,864	3,713,042	0.3219
MSCPRA -51ft	-53	416,866	79,583	0.0069
MSCPRA -47ft	-49	6,773,141	925,613	0.0803
PRA	-49	15,406,346	3,558,324	0.3085
MSCRCA	-49	8,652,469	2,099,269	0.1820
Reserved Channel	-49	2,054,393	530,046	0.0460
Turning Basin	-49	1,213,506	336,289	0.0292
MSCMMT	-47	1,696,047	291,050	0.0252
Total		48,967,632	11,533,216	1.0000

Table 25b lists the volume of all material per reach. The fractions were calculated per reach for all materials for all reaches.

Table 25b. Estimates of all areas and volumes above the second 2ft overdepth. The fractions are per reach.

	Second overdepth	Area above second overdepth in case of hard bottom	Volume above second overdepth in case of hard bottom	Fraction of total volume
Reach	ft, MLLW	sqft	cuyd	
North Channel	-55	12,775,760	3,987,054	0.3316
MSCPRA -51ft	-55	416,867	79,583	0.0066
MSCPRA -47ft	-51	7,066,946	925,775	0.0770
PRA	-51	15,463,165	3,567,733	0.2967
MSCRCA	-51	8,654,303	2,178,640	0.1812
Reserved Channel	-51	2,054,393	586,902	0.0488
Turning Basin	-51	1,213,506	350,368	0.0291
MSCMMT	-49	1,696,047	347,254	0.0289
Total		49,340,986	12,023,310	1.0000

Table 26 reorganizes the estimates into the required volumes consisting of sum of the volume above newly authorized grade and the required overdepth in the case of the rock or hard bottom.

Table 26. Estimates of required volumes to grade and required overdepth. The fractions are per reach.

	Grade	Total volume to grade including side slopes	Volume of till/rock from grade to OD 1	Volume of sediment in areas of till/rock from grade to first overdepth	Total
Reach	ft, MLLW	cuyd	cuyd	cuyd	cuyd
North Channel	-51	2,686,253	250,677	11,395	2,948,325
MSCPRA -51ft	-51	47,672	0	0	47,672
MSCPRA -47ft	-47	473,226	8	20	473,255
PRA	-47	2,384,733	2,666	1,909	2,389,307
MSCRCA	-47	1,321,583	57,500	7,842	1,386,925
Reserved Channel	-47	356,346	39,146	5,917	401,408
Turning Basin	-47	235,649	7,840	1,870	245,359
MSCMMT	-45	150,740	39,228	8,803	198,771
Total		7,656,200	397,065	37,757	8,091,022