Sediment Classification and the Characterization, Identification, and Mapping of Geologic Substrates for the Glaciated Gulf of Maine Seabed and Other Terrains, Providing a Physical Framework for Ecological Research and Seabed Management

Scientific Investigations Report 2019–5073

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U.S. Geological Survey
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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.5400	mile, nautical (nmi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.2916	square nautical mile (nmi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)

Datum

Elevation, as used in this report, refers to depth of water from sea level.

Sediment Classification and the Characterization, Identification, and Mapping of Geologic Substrates for the Glaciated Gulf of Maine Seabed and Other Terrains, Providing a Physical Framework for Ecological Research and Seabed Management

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Abstract

A geologic substrate is a surface or volume of sediment or rock where physical, chemical, and biological processes occur, such as the movement and deposition of sediment, the formation of bedforms, and the attachment, burrowing, feeding, reproduction, and sheltering of organisms. Seabed mapping surveys in the Stellwagen Bank region off Boston, Massachusetts, from 1993 to 2004 have led to the development of a methodology for characterizing, identifying, and mapping geologic substrates. The resulting high-resolution interpretive maps (1:25,000) show the distribution of substrates in a glaciated terrain of banks and basins in water depths of 30 to 185 meters. Data sources used to characterize substrates are multibeam sonar bathymetric and backscatter imagery to document seabed topography and patterns of sediment and rock distribution, grain-size analyses of sediment samples to determine substrate composition, and video and photographic imagery of the seabed to aid in the interpretation of multibeam sonar imagery and to provide information on substrate layering and mobility, seabed structures, and sediments and nonsediment materials that cannot be physically sampled.

Sediment composition is a major property of many seabed substrates. Sediment grains belong to a continuum of grain-diameter sizes previously classified into grades (for example, fine sand, medium sand) and into aggregates (mud, sand, gravel). The definition of grade and aggregate boundaries in a classification is arbitrary, and a useful classification is limited to as few classes as are needed to effectively organize and apply information. For the purpose of mapping substrates, sediment grades and aggregates were simplified and re-classified into eight composite grades based on grain-size content, mode of transport, and ecological role. Five composite grades are identified using grain-size analysis and three are identified using video and photographic imagery of the seabed.

Naturally occurring sediments contain various amounts of the aggregates mud, sand, and gravel. The separation of naturally occurring sediments into sediment classes, based on grain-size analysis, requires that limits be set on the amount of mud, sand, and gravel each class contains. Fifteen previously identified basic sediment classes provided interpretive information on sediment transport by emphasizing gravel content (a low 0.01-weight-percent threshold) and on winnowing processes based on the sand-to-mud ratio. The present study recognizes 20 basic sediment classes that are combinations of aggregates in which the lower limits for recognition of mud and sand are 10 weight percent and of gravel, 25 weight percent. These sediment classes can be made more specific by listing their content of the composite grades fine-grained sand (3 and 4 phi), which is transported in suspension, and coarse-grained sand (0, 1, and 2 phi), which is transported as bedload. Additional sediment classes and nonsediment classes that cannot be sampled are recognized on the basis of visual analysis of seabed video and photographic imagery and include pebble, cobble, and boulder gravel, rock outcrops, and shell beds, among others.

Substrates are not classified because their properties are too varied for a classification to be concise and useful. Rather, substrates are characterized and identified by sediment grain-size composition (the sediment class); the distribution, in millimeters, of grain diameters in the sediment; the presence of nonsediments (for example, rock outcrops); substrate mobility based on the presence of sediment ripples; substrate layering (for example, a partial veneer of sand on gravel); and seabed structures. These properties have interpretive value by providing information about sedimentary processes acting on a substrate and about its ecological function. A geologic substrate, when it is associated with one or more species, is an important element of a habitat.

This methodology was developed to map a glaciated terrain characterized by geologic substrates that typify a wide range of erosional and depositional sedimentary environments, and it likely will be useful for mapping substrates in other terrains. Substrate maps provide the physical framework required for identifying sediment transport processes,

validating sediment transport models, studying the ecology of species and communities, and managing marine resources and seabed usage.

Introduction

The development of modern methods for imaging and sampling sea floor environments has made it possible to create high-resolution interpretive maps of seabed properties. Although advanced multibeam sonar systems produce bathymetric and backscatter imagery that show seabed features in great detail, physical sampling is still required to provide the groundtruth information needed to interpret the imagery and identify geologic substrates. A major goal of seabed analysis is to describe and map geologic substrates in a manner that improves our understanding of the relation between the physical properties of the seabed and the species that use it. Substrates occur in a wide variety of ecological settings, and the term substrate has meaning for biologists who study relations between organisms and their environments. Once described and mapped, substrate properties will provide the physical framework necessary for studying the ecology of benthic species and communities and for managing the seabed.

This report presents a modified approach to seabed classification as described by Valentine and others (2005) by focusing on the characterization of geologic substrates alone, not on habitats. The principles described here for characterizing substrates were developed by mapping quadrangle 6 of the Stellwagen Bank National Marine Sanctuary region (fig. 1),[1] a heterogeneous, glaciated bank and basin terrain of 211 square kilometers (km^2) off Boston, Massachusetts. The diversity of seabed properties in this quadrangle make it an area suitable for developing a methodology to characterize and map substrates. Quadrangle 6 (Valentine and Gallea, 2015) is composed of 10 substrates that range from muddy sand to immobile sand to rippled sand to boulder ridges in water depths of 30 to 185 meters (m). A similar mapping effort is being applied to a wider region of the Gulf of Maine, including quadrangle 5 to the west.

The substrate characterization process utilizes information from a suite of physical properties that are common to substrates, including sediment grain-size composition and distribution of grain diameters, nonsediments (for example, rock outcrops), substrate mobility as determined by the presence of sediment ripples, substrate layering (for example, an upper rippled sand substrate partially veneering a lower gravel substrate), and seabed structures (for example, burrows, bedforms, boulder piles). This information is acquired through grain-size analysis of sediment samples and visual interpretation of multibeam sonar, video, and photographic imagery of the seabed. The mapping process resulted in the simplification of the grade classification of sediment grain sizes developed by Udden (1914) into fewer composite grades and the development of a new classification of naturally occurring sediments into sediment classes that differ from those developed by Folk (1954, 1980).

This approach facilitates the characterization of geologic substrates and the determination of their potential ecological usage by organisms by using the newly defined composite grades for sand and gravel, placing less emphasis on gravel content than Folk (1954, 1980), and providing information on the mode of transport of the sand component (for example, fine-grained sand moves in suspension and coarse-grained sand is stationary or moves as bedload). It relies on video and photographic imagery to identify pebble, cobble, and boulder gravel and nonsediment substrates.

The compilation of substrate maps requires (1) characterization of substrates based on their physical properties and development of a suite of standard descriptors, (2) identification of substrates based on the presence of the descriptors, (3) mapping of geologic substrates, and (4) compilation of thematic maps to show the physical properties of each substrate in terms of substrate mobility and the distribution of sand and mud content. The objective is to map substrates at a scale that provides information for a variety of uses that is justified by the resolution and density of sonar imagery, sediment grain-size analyses, and video and photographic observations. The mapping methodology developed for a heterogeneous, glaciated terrain should be also applicable to other terrains.

Habitats Versus Substrates

Definition of Habitat

It is useful to understand how the concepts of habitat and geologic substrate relate to each other. The definition of the fundamental ecological concept of "habitat" has varied over time. Charles Darwin (1872, p. 434) defined habitat as "the locality in which a plant or animal naturally lives." This is interpreted here to mean that the "locality" is a geographic place whose environment allows a particular species or group of species to exist. Hall and others (1997) reviewed the use of habitat terminology in the scientific literature and concluded that "habitat is organism-specific" and should be defined "as the resources and conditions present in an area that produce occupancy … by a given organism." This view is followed here. Dennis and others (2003, fig. 2) viewed habitat as functional and resource based and recognized that a species can reside in different habitats seasonally and use different areas of a habitat daily to perform the functions of feeding, breeding, sheltering, and migrating. For further discussion of the development of habitat definitions and terminology, see Dauvin and others (2008a, b), Elliott and others (2016), Olenin and Ducrotoy (2006), and references therein.

[1]Callouts to figures and tables have been hyperlinked to the location of the figure or table. Press and hold the Alt key followed by the left arrow key to return to the original page in the document after following the hyperlink.

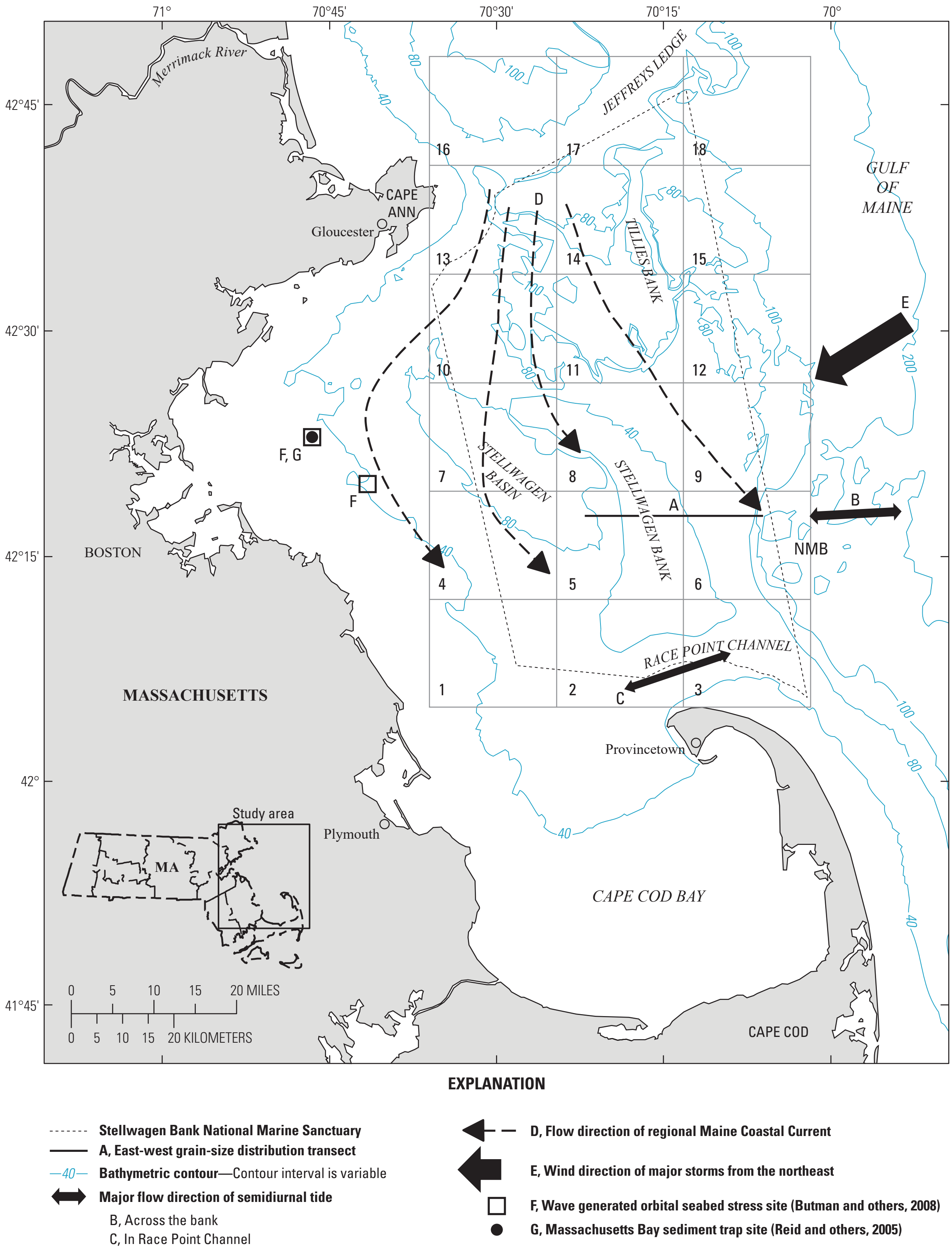


Figure 1. Locations of glaciated banks and basins and hydrographic processes in the Stellwagen Bank region east of Boston, Massachusetts. The numbered grid outlines the U.S. Geological Survey substrate mapping project in the region that has been imaged using multibeam sonar technology. Cross sections of transect A are shown in figure 4. NMB, Ninety Meter Banks.

Definition of Substrate

A substrate is defined as “the substance, base, or nutrient on, or medium in which an organism lives and grows, or the surface to which a fixed organism is attached …” (Gary and others, 1972). Expanding on this definition, in this study a geologic substrate is defined as a surface or volume of sediment or rock where physical, chemical, and biological processes occur, such as the movement and deposition of sediment, the formation of bedforms, and the attachment, burrowing, feeding, reproduction, and sheltering of organisms. The water column and its properties is a nongeologic substrate. A geologic substrate is but one element of an organism’s habitat, and, paraphrasing Hall and others (1997), it provides some of the resources and conditions that produce occupancy by a species.

Classification of Sediment Grains by Size—Grades and Aggregates

Classification is the process of arranging things (for example, sediment grains) into groups based on their properties, and choices must be made as to how to define group boundaries. Udden (1914) classified clastic sediment grains by their grain diameters into 19 grades based on his arbitrary decision to double the grain-diameter range of each coarser grade (fig. 2; table 1). Udden’s sequence of grain diameters extends from 0.0005 to 256 millimeters (mm). Later, Blair and McPherson (1999) added four grades (extending from 256 to 4,096 mm) to the coarse end of the Udden classification, to give a total of 23 grades that range from clay particles to boulders. This is the standard for classifying sediment grains by size. The names of the sediment grades (for example, fine sand, coarse sand; see fig. 2, columns 3 and 4) have evolved since Udden’s initial proposal and now include names proposed by Udden (1914), Wentworth (1922), and Blair and McPherson (1999).

The grain-size boundaries of the Udden classification expressed in millimeters were converted by Krumbein (1936) into a sequence of whole numbers called phi (φ) values, where phi is the logarithm of the grain diameter (d) and is found using the formula $\varphi = -\log_2 d(\text{mm})$ (fig. 2). An artefact of the phi grade classification that can confuse nongeologists is that grains >1 mm in diameter are expressed as negative phi values. For example, the granule gravel grade (2 to <4 mm) of Wentworth (1922) contains grains ranging from −1 to <−2 phi. Significantly, the phi grade scale conceals the doubling of the range of grain diameters (in millimeters) as sediments coarsen in the grade classification scheme of Udden (1914).

Wentworth (1922, tables 1 and 2) combined all sediment grades defined at that time into four aggregates (clay, silt, sand, gravel) and subdivided the gravel aggregate into a granule gravel grade and three grades of pebble gravel, cobble gravel, and boulder gravel. The pebble, cobble, and boulder gravel grades of Wentworth are here renamed composite grades (fig. 2) because they were later subdivided into 10 grades by Blair and McPherson (1999, fig. 2). Folk (1954) combined the clay and silt aggregates into the mud aggregate.

Classification of Naturally Occurring Sediments—Sediment Classes

The classification of naturally occurring sediments produces sediment classes (table 1), a major component of many seabed substrates. In designing a classification, it must be remembered that arbitrary choices are made to define class limits, and the purpose of the classification guides its structure. According to Wentworth (1922, p. 390) and Folk (1954, p. 345), a useful classification of naturally occurring sediments, based on grain-size analysis, should find a balance between being too simple (too few classes) and too complex (too many classes). Wentworth points out that the quantitative detail of the composition of each sediment class can be described better in tables than in verbal terminology.

Wentworth’s classification of naturally occurring sediments contains 10 sediment classes defined by the weight percent content of the aggregates (clay, silt, sand, gravel) they contain and are named using two terms at most (Wentworth, 1922, p. 390). The weight percent content of each aggregate is treated equally by Wentworth in defining class boundaries. The lower limit for an aggregate to be included in a sediment class is >10 weight percent. For example, a sediment with gravel > sand > 10 weight percent, and other aggregates <10 percent, is a sandy gravel. His classification was not meant to be inclusive, and he did not include highly mixed sediments such as glacial till in his scheme.

Folk’s classification of naturally occurring sediments contains 15 sediment classes he called textural classes or textural groups (fig. 3) that, following Wentworth, are also defined by the weight percent content of the aggregates (mud, sand, gravel) they contain (Folk, 1954, fig. 1a, table 1; 1980, p. 25–28, table 1). Note that Folk combines silt and clay into a mud aggregate. By contrast with the Wentworth classification, which gives equal weight to clay, silt, sand, and gravel content, Folk designed sediment classes to reveal the effects of transport on sediment grains. The most important criterion is the gravel content, to emphasize its importance as an indicator of the velocity of the current from which the sediment was deposited. Sediments with only 0.01 to <5 weight percent gravel are classified as slightly gravelly, and sediments with ≥30 weight percent are classified as gravel. The second most important criterion is the sand-to-mud ratio that documents the effects of winnowing after deposition. The basic 15 sediment classes can be expanded to number several hundred by incorporating properties such as the median grain size of the gravel and sand fractions, the silt to clay ratio, and the degree of sorting of the sand classes (Folk, 1980, table 1).

<table>
<tr><th colspan="4">Sediment grade</th><th colspan="2" rowspan="2">Sediment aggregates and abbreviations</th><th rowspan="2">Composite gravel grades</th><th colspan="2">Composite sediment grades of this study and abbreviations</th></tr>
<tr><th>Grain-diameter range, in mm</th><th>Scale, phi</th><th>Citation of grade name</th><th>Grade name</th><th>Based on grain-size analysis of sediment samples</th><th>Based on visual analysis of seabed imagery</th></tr>
<tr><td>2,048 to <4,096</td><td>−11</td><td rowspan="10">Blair and McPherson (1999)</td><td>Very coarse boulder gravel</td><td colspan="2" rowspan="11">Gravel G</td><td rowspan="4">Boulder gravel</td><td rowspan="6"></td><td rowspan="4">Boulder gravel bG</td></tr>
<tr><td>1,024 to <2,048</td><td>−10</td><td>Coarse boulder gravel</td></tr>
<tr><td>512 to <1,024</td><td>−9</td><td>Medium boulder gravel</td></tr>
<tr><td>256 to <512</td><td>−8</td><td>Fine boulder gravel</td></tr>
<tr><td>128 to <256</td><td>−7</td><td>Coarse cobble gravel</td><td rowspan="2">Cobble gravel</td><td rowspan="2">Cobble gravel cG</td></tr>
<tr><td>64 to <128</td><td>−6</td><td>Fine cobble gravel</td></tr>
<tr><td>32 to <64</td><td>−5</td><td>Very coarse pebble gravel</td><td rowspan="4">Pebble gravel</td><td rowspan="3">Gravel$_2$ G_2</td><td rowspan="5">Pebble gravel pG</td></tr>
<tr><td>16 to <32</td><td>−4</td><td>Coarse pebble gravel</td></tr>
<tr><td>8 to <16</td><td>−3</td><td>Medium pebble gravel</td></tr>
<tr><td>4 to <8</td><td>−2</td><td>Fine pebble gravel</td><td rowspan="2">Gravel$_1$ G_1</td></tr>
<tr><td>2 to <4</td><td>−1</td><td rowspan="2">Wentworth (1922)</td><td>Granule gravel</td><td rowspan="13"></td></tr>
<tr><td>1 to <2</td><td>0</td><td>Very coarse sand</td><td colspan="2" rowspan="5">Sand S</td><td rowspan="3">Coarse-grained sand cgS</td><td rowspan="12"></td></tr>
<tr><td>0.5 to <1</td><td>1</td><td rowspan="11">Udden (1914)</td><td>Coarse sand</td></tr>
<tr><td>0.25 to <0.5</td><td>2</td><td>Medium sand</td></tr>
<tr><td>0.125 to <0.25</td><td>3</td><td>Fine sand</td><td rowspan="2">Fine-grained sand fgS</td></tr>
<tr><td>0.062 to <0.125</td><td>4</td><td>Very fine sand</td></tr>
<tr><td>0.031 to <0.062</td><td>5</td><td>Coarse silt</td><td rowspan="7">Mud M</td><td rowspan="4">Silt</td><td rowspan="7">Mud M</td></tr>
<tr><td>0.015 to <0.031</td><td>6</td><td>Medium silt</td></tr>
<tr><td>0.008 to < 0.015</td><td>7</td><td>Fine silt</td></tr>
<tr><td>0.004 to <0.008</td><td>8</td><td>Very fine silt</td></tr>
<tr><td>0.002 to <0.004</td><td>9</td><td>Coarse clay</td><td rowspan="3">Clay</td></tr>
<tr><td>0.001 to <0.002</td><td>10</td><td>Medium clay</td></tr>
<tr><td>0.0005 to <0.001</td><td>11</td><td>Fine clay</td></tr>
</table>

Figure 2. Classifications of sediment grains, sediment grades, composite sediment grades, and sediment aggregates. See table 1 for definitions of the terms grade, aggregate, and composite grade. Phi grade value (column 2) represents the lower limit of its equivalent millimeter grade range (column 1); the mud aggregate (column 5) is the same as the mud composite grade (column 7); the cobble gravel and boulder gravel composite grades (column 6) are the same as the cobble gravel and boulder gravel composite grades (column 8); and the granule gravel grade (column 4) is part of the gravel$_1$ composite grade (column 7) and the pebble gravel composite grade (column 8). Three aggregates shown in italics (column 5) are the components of sediment classes shown in figures 3 and 5. Grain-diameter range is based on the scheme of Udden (1914) converted to decimal values from fractions; the phi scale is based on the scheme of Krumbein (1936); the composite gravel grades and the gravel, sand, silt, and clay sediment aggregates are from Wentworth (1922); and the mud sediment aggregate is from Folk (1954). mm, millimeter.

Table 1. Definitions and origins of the terms sediment grade, composite sediment grade, sediment aggregate, sediment class, and substrate.

[Refer to the text for further explanation and to figure 2 for grain-size ranges of grades, composite grades, and aggregates]

Term	Definition and origin
Sediment grade	A group of sedimentary grains (identified by grain-size analysis) that is part of a classification sequence of 23 grades each of whose grain-size range, in millimeters, doubles as grain diameters increase (a scheme developed by Udden, 1914). Grades based on this scheme were named by Udden (1914), Wentworth (1922), and Blair and McPherson (1999). Grades expressed in millimeters were converted to the phi scale by Krumbein (1936). The phi grade scale conceals the doubling of the range of grain diameters in the millimeter grade classification. Grades are based on grain size only; they do not necessarily have interpretive meaning. It is unlikely that a naturally occurring sediment, described as a sediment class (see below), is represented by just one grade.
Composite sediment grade	A term proposed here to describe a group of sedimentary grains formed by combining two to seven sediment grades into composite sediment grades (fig. 2) to simplify the grade classifications of Udden (1914), Wentworth (1922), and Blair and McPherson (1999), and to add interpretive meaning to the classification (for example, coarse-grained sand moves as bed load, and fine-grained sand moves as suspended load). Note that the pebble, cobble, and boulder gravel grades of Wentworth (1922, tables 1 and 2) are renamed composite grades because they were subdivided into 10 grades (fig. 2) by Blair and McPherson (1999, fig. 2). Examples of composite sediment grades identified by grain-size analysis are mud (seven grades), fine-grained sand (two grades), coarse-grained sand (three grades), $gravel_1$ (two grades), and $gravel_2$ (three grades). Examples of composite sediment grades based on visual analysis of seabed imagery are pebble gravel (five grades), cobble gravel (two grades), boulder gravel (four grades). Composite sediment grades can occur as sediment classes.
Sediment aggregate	Sediment grades were grouped into one of four aggregates: clay, silt, sand, and gravel by Wentworth (1922). Clay and silt were combined into the mud aggregate by Folk (1954). Aggregates can occur as naturally occurring sediment classes. Aggregates have interpretive value (for example, mud and gravel grains move differently and play different ecological roles on the seabed).
Sediment class	A natural mixture of sediment grains. A sediment class (based on grain-size analysis) is not defined by a specified range of grain sizes (as is a grade or an aggregate) but by the weight percents of the aggregates and composite grades it contains. Sediment classes have interpretive value. Wentworth (1922, p. 390) classified naturally occurring sediments into 10 sediment classes. He defined the classes by the weight percent of each of four aggregates (clay, silt, sand, gravel) in the sediment. Folk (1954, table 1; 1980, p. 25–28) classified natural sediments into fifteen textural classes based on the weight percent of three aggregates (mud, sand, gravel) in the sediment (fig. 3). Folk's classes can be modified and increased in number by adding terms that describe the median grain size of both the gravel and sand aggregates expressed in grade terms (for example, pebbly coarse sand), the ratio of silt to clay, and the degree of sorting. In the substrate component of the Coastal and Marine Ecological Classification Standard (Federal Geographic Data Committee, 2012), Folk's classes are renamed "substrate groups and subgroups," but the definition of their sediment content is unchanged. The British Geological Survey (Long, 2006) and the European Marine Observation and Data Network (Kaskela and others, 2019) reduced Folk's 15 sediment classes to as few as four to facilitate mapping seabed sediment distributions at scales of 1:250,000 and 1:1,000,000. In this study, sediment classes are defined by the weight percent of their aggregates (mud, sand, gravel; fig. 5) and, when more specificity is needed, by the weight percent of their composite grades (fine- and coarse-grained sand, $gravel_1$, $gravel_2$; table 8). Sediment and nonsediment classes that cannot be sampled are identified based on qualitative visual analysis of seabed imagery. See tables 5 to 7 and 9 for full descriptions of sediment and nonsediment classes. Here, a sediment class is not a substrate; it is one of several properties used to characterize and identify a substrate.
Geologic substrate	A surface or volume of sediment or rock where physical, chemical, and biological processes occur, such as the movement and deposition of sediment, the formation of bedforms, and the attachment, burrowing, feeding, reproduction, and sheltering of organisms. Substrate properties (descriptors) include: grain-size composition (sediment class); distribution of grain diameters in the sediment; nonsediment class; substrate mobility; substrate layering; and seabed structures. Nongeologic descriptors characteristic of a seabed substrate that are useful in its identification and mapping, such as water depth, can be utilized as appropriate.

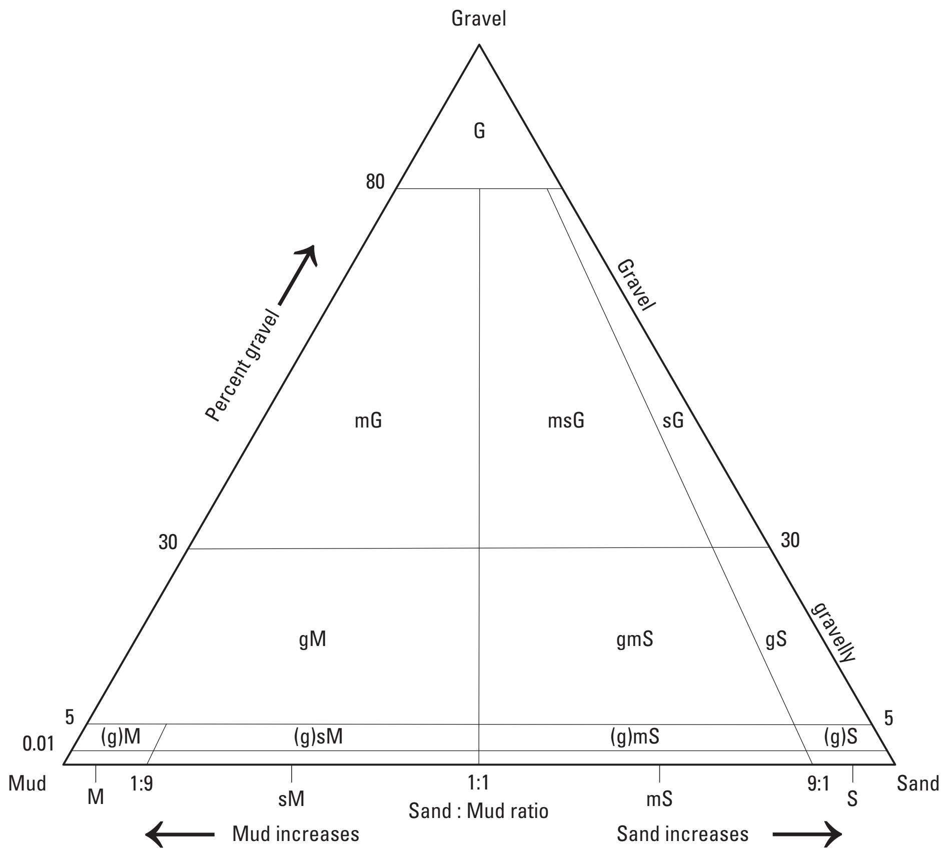


Figure 3. Triangular diagram showing grain-size composition of 15 naturally occurring sediments (textural classes of Folk, 1954, 1980) based on weight percent of their aggregates (mud, sand, and gravel) content as determined by grain-size analysis (some labels outside the triangle have been added). The threshold for the recognition of gravel is greater than or equal to 0.01 weight percent. The gravel axis is shown to scale except for the 0.01 value. The gravel axis is not shown to scale in Folk (1954, fig. 1a; 1980, p. 26). See Long (2006) and Kaskela and others (2019) for modifications of Folk's sediment classes. M, mud; m, muddy; S, sand; s, sandy; G, gravel; g, gravelly; (g), slightly gravelly.

For example, a slightly gravelly muddy sand with modifiers becomes a poorly sorted, slightly pebbly, silty, medium sand.

The Folk (1954, 1980) classification of sediments is identical to the classification of "unconsolidated mineral substrate" of the Coastal and Marine Ecological Classification Standard (CMECS; Federal Geographic Data Committee, 2012). The CMECS retains all of the threshold values of mud, sand, and gravel content proposed by Folk for classifying sediments. The major difference between the two classifications is the change in terminology that resulted by the renaming of Folk's 15 sediment classes as CMECS substrate groups and subgroups (Federal Geographic Data Committee, 2012, p. 105–108, fig. 7.2).

Folk's sediment classification has been simplified several times for the purpose of mapping European seabed sediments at regional scales of 1:250,000 and 1:1,000,000. The British Geological Survey (BGS) combined Folk's 15 classes into 11 or 4 classes (Long, 2006, figs. 1–4). During this process, the lower limit for recognizing gravel was raised from the 0.01 weight percent of Folk to 1 and then to 5 weight percent, and the boundary between sandy mud and muddy sand was redefined. This approach deemphasized the gravel content of the sediment and emphasized the mud content.

The European Marine Observation and Data Network (EMODnet) uses a modified Folk classification, similar to that of the BGS described by Long (2006), for mapping seabed sediments at scales of 1:250,000 and 1:1,000,000 (Kaskela and others, 2019, fig. 3). EMODnet simplified Folk's 15 sediment classes into 6 or 4 classes and added a "rock and boulders" class. The EMODnet maps of the European seas show the distribution of sediments using the following five sediment classes: mud to muddy sand, sand, mixed sediment, coarse sediment, and rock and boulders (Kaskela and others, 2019, figs. 6 and 7).

Barnhardt and others (1998) designed a seabed "bottom type" classification of the Maine coastal region based primarily on interpretation of side-scan sonar imagery supplemented by limited groundtruthing using sediment sampling, coring, and video imagery collected by submersibles. This classification contains 16 bottom types composed of four components (rock, gravel, sand, mud) and was developed to allow mapping at a scale of 1:100,000 of a topographically irregular, glaciated seabed that is a mix of sediments and bedrock outcrops. The four components of the classified bottom types are given equal weight in this classification, similar to Wentworth's (1922) approach. Seabeds are classified as rock, gravel, sand, or mud if one of these components composes >90 percent of the area of a mappable unit. Seabeds are classified as composite units if one of the four components makes up ≥50 percent and ≤90 percent and another component makes up <50 percent of the unit by area. For example, if sand constitutes ≥50 of a map unit by area and gravel <50 percent, the bottom type (symbol Sg) is termed "sand with subordinate gravel" (Barnhardt and others, 1998, fig. 2).

Regional Setting

Deglacial History

The deglacial history of the Gulf of Maine provides information necessary for interpreting the glacial origin and subsequent modification of the seabed materials in the Stellwagen Bank region. The events described here follow reconstructions of the final deglaciation of the Gulf of Maine and Atlantic Canada by Shaw and others (2002, 2006) whose maps show the locations of glacier margins through time.

The Gulf of Maine is a large, deep embayment of the United States and Canadian coasts that is separated from the Atlantic Ocean by two large shallow banks (Georges Bank and Browns Bank) that form the continental shelf (Shaw and others, 2006, fig. 1). There is some evidence for pre-Wisconsinan glaciations in the Gulf of Maine region (Stone and Borns, 1986; Siegel and others, 2012). However, the topography of the gulf's deep basins and bounding ridges is interpreted to have formed primarily by the eastward advance of the Wisconsinan Laurentide Ice Sheet and subsequently modified by processes of deglaciation.

The Laurentide Ice Sheet reached its maximum extent (the Last Glacial Maximum) approximately (~) 22 thousand years before present time (ka BP) on the shallow continental shelf that separates the Gulf of Maine from the deep waters of the Atlantic Ocean (Shaw and others, 2006, fig. 8). By 20 ka BP, the ice sheet margin was breaking up, receding westward by melting, and opening the gulf to the waters of the Atlantic Ocean. By 16 ka BP, the ice sheet margin was off the present coast of Massachusetts in the region of Stellwagen Bank (Shaw and others, 2006, figs. 9–11).

Diverse glacial features, which include lateral and end moraines, eskers, kettles, crevasse splays, ice fall deposits, and iceberg plow marks were observed in multibeam sonar imagery of the Stellwagen Bank region and described in a series of 18 topographic maps (fig. 1; Valentine and others, 2010). On the southeastern margin of Stellwagen Bank, lateral moraines and an ice fall deposit are present to a depth of ~180 m below present sea level in quadrangle 6 (fig. 1) and are interpreted here to have originated at the margin of the melting ice sheet at ~16 ka BP as mapped by Shaw and others (2006, fig. 11). The presence of these features supports the hypothesis of Oldale and others (1990) that the melting ice sheet was grounded, in contrast to the interpretation of Schnitker and others (2001) who hypothesized that the glacier receded from the Gulf of Maine as a floating ice shelf.

The most rapid period of deglaciation occurred from ~16.5 to ~7 ka BP (Lambeck and others, 2014). By 14 ka BP, the ice sheet margin had receded onto the present land area of southeastern Massachusetts, and the glacial features of the Stellwagen Bank region had their first submergence by the rising sea (Shaw and others, 2006, fig. 12). By 13 ka BP, the ice sheet margin had receded farther westward to the New England coastal uplands (Shaw and others, 2006, fig. 13), and the present coastal region from Massachusetts to Maine, which had been depressed by the weight of the melted ice, was flooded by the sea and covered by glaciomarine mud deposited from meltwater (Bloom, 1963; Oldale and others, 1990). It is likely that this marine mud forms the floors of the present nearshore basins. It is not known whether this mud was also deposited on Stellwagen Bank; however, outcroppings of semiconsolidated, burrowed mud were observed on the bank during the present study but could not be sampled.

By 12 ka BP, the depressed, submerged New England coastal region experienced crustal rebound in response to removal of the ice load, which caused the rising of the seabed, the eastward retreat of the sea, and the lowering of sea level (Shaw and others, 2006, fig. 14). In addition, by 11 ka BP, in a further response to removal of the ice, a bulge in the Earth's crust, which had formed in front of the ice sheet (the forebulge), migrated westward resulting in additional rise of the present coastal region and further fall of sea level (Barnhardt and others, 1995). This caused the emergence of some nearshore areas, including Stellwagen Bank (Shaw and others, 2002, fig. 9).

The timing and magnitude of this lowstand of sea level and emergence of the bank seem to have varied along the present coastal region from Massachusetts in the south to Maine in the north. Oldale and others (1993) suggest that the lowstand along the Massachusetts coast occurred earlier, at ~12 ka BP, and reached ~45 m below present sea level. Barnhardt and others (1995), whose sea-level curve is better documented than that of Oldale and others, suggest the maximum sea level fall along the Maine coast occurred somewhat later, from 11 to 10.5 ka BP, and that sea level reached ~55 m below present sea level. Significantly, both interpretations indicate the lowstand caused the shallowest part of Stellwagen Bank (presently −20 m on the Southwest Corner) to be exposed to a height of ~25 to ~35 m above present sea level. The effect of the forebulge ended after 10.5 ka BP, and eustatic sea level rose so that, by ~8 ka BP, the bank experienced its second submergence (Oldale and others, 1990; Barnhardt and others, 1995; Shaw and others, 2002, fig. 12).

In summary, the glaciated Stellwagen Bank region, especially the bank itself, has experienced three periods of erosion associated with rising and falling sea levels since the Last Glacial Maximum. The region was eroded first ~14 ka BP by the rising sea that followed the westward-melting glacial front. The bank was eroded a second time at ~11 ka BP by a falling sea when crustal rebound and a westward-migrating forebulge caused the low-stand emergence, and a third time at ~8 ka BP by eustatic sea level rise that finally submerged it. During these three periods, submarine and subaerial erosive processes likely modified glacial features; altered the grain-size composition of glacially derived sediment (often mixes of mud, sand, and gravel); and determined, in large part, the character of present-day substrates. In shallow water, substrates continue to be reworked by episodic storms from the northeast that affect the Stellwagen Bank seabed to a depth of ~50 m.

Seabed Topography and Present Hydrographic Conditions

The Stellwagen Bank region is part of a bank and basin marine ecosystem that occupies a glaciated seabed in the southwestern part of the Gulf of Maine. It extends eastward off the coast of Massachusetts for approximately 60 km and is bounded on the south by Cape Cod and on the north by Cape Ann, which lie 65 km apart (fig. 1). Regional seabed topography is highly complex and is characteristic of a now-submerged glaciated terrain produced by processes associated with the advance and subsequent melting of the Wisconsinan Laurentide Ice Sheet (Shaw and others, 2002, 2006).

Stellwagen Bank is a shallow, elongated (north to south) bank located ~35 km east of Boston. It is asymmetrical in east-west cross section, with a gently sloping eastern flank and a steeper western flank. The bank's southern and shallowest (20-m water depth) margin lies ~4 km north of Cape Cod from which it is separated by Race Point Channel (60 m). The seabed is covered to a water depth of 50 m by bedforms of coarse-grained sand. Sediment below 50 m becomes increasingly fine grained with depth. The bank is bounded to the west by Stellwagen Basin, a deep, muddy basin 80 to 100 m in depth that separates the bank from Massachusetts coastal areas. The bank is bounded to the east by a broad coarse-grained ramp of sand and gravel 70 to 80 m in depth, and to the southeast by a cluster of small banks, the Ninety Meter Banks, whose surfaces of sand and gravel lie at a depth of 90 m and which are separated by muddy basins that reach a depth of 185 m.

The waters of the Stellwagen Bank region (fig. 1), as described by Butman and others (2007), are transported by a weak, semidiurnal tidal current whose strongest flow (~50 centimeters per second [cm/s]) is east-west across the bank. The tidal current on the bank is stronger than in other parts of the region, except in Race Point Channel to the south (60–70 cm/s) where it is enhanced by local topography. A regional current from the north, the Maine Coastal Current (MCC), flows south and southeast into Massachusetts Bay and across Stellwagen Bank at 5 to 10 cm/s. Tidal and MCC currents combine to produce a regional mean surface flow of 3 to 7 cm/s in winter and 8 to 10 cm/s in summer that mimics the flow pattern of the MCC.

Episodic storm winds from the northeast, usually in winter and often lasting days, generate waves that reach periods of up to 13 seconds and significant heights of 4 to 5 m (Butman and others, 2008). Storm-generated wave-orbital currents resuspend fine-grained particles from the bank's seabed that are transported by tidal and wind-driven flow westward into Stellwagen Basin (Warner and others, 2008). Substrate mapping has shown that these storm currents disturb the seabed to a water depth of ~50 m and form large bedforms with amplitudes of up to 30 cm and wavelengths of up to 1 m. The bedforms impart a ruggedness to the seabed that persists through nonstorm periods, except where they are flattened by bottom trawls and scallop dredges.

The glaciated terrain is being preserved because little or no sediment from land sources is deposited in the basins nearshore, and the banks and offshore basins receive none. The Merrimack River (fig. 1) is the largest potential source of sediment for the region, but its bedload of sand is deposited nearshore to form barrier islands (FitzGerald and others, 2002, 2005), and most of its suspended load likely is deposited on the tidal flats of its estuary (Hartwell, 1970).

Sediment Transport Processes and the Movement of Sediment Grains in the Region

Sediment Resuspension and Transport Predicted by Analysis of the Effects of Storm Wave and Tidal Currents on the Seabed

The predictions of sediment transport models show that tidal currents alone generally are too weak to transport sediments in the Massachusetts Bay and Stellwagen Bank regions; but that the wave-orbital currents generated by major storms from the northeast quadrant can resuspend sediment and, aided by tidal and wind-driven currents, cause periodic erosion of the bank (Butman and others, 2008; Warner and others, 2008). Wave-generated orbital seabed stress was calculated from wave data collected at sites in Massachusetts Bay over 17 years from 1990 through 2006 (Butman and others, 2008, table 2a). The study sites in Massachusetts Bay (fig. 1) lie west of Stellwagen Bank in water depths of 30 and 55 m, similar to depths on the bank where storm-generated sand ripples occur. Stress values for each of the 25 strongest storms averaged 0.27 to 1.38 pascals (Pa) and reached maxima of 0.6 to 5.23 Pa; all the storms produced wave-orbital seabed stresses large enough to resuspend sediment particles of at least 3 phi (0.125 mm) in diameter in water depths of 30 m.

Sediment transport modeling by Warner and others (2008, fig. 13) along a transect across the bank just north of transect A (fig. 1) predicted deposition of 4-phi sand on the western flank of the bank, 5- and 6-phi silt in the basin, and a lag of 1-, 2-, and 3-phi sand on the bank. The model correctly predicted the distribution of 1-, 2-, 4-, 5-, and 6-phi sediment, as confirmed by their distributions along the sampled transect A of this study (see section "Simplification of the Traditional Five-Grade Sand Classification into Two Composite Grades, Fine-Grained Sand and Coarse-Grained Sand"). The predicted lag of 3-phi sand on the bank does not agree with the sampled distribution, which shows a very low concentration of it there. The model did not include grains of 0 phi, which constitute 20 to 30 weight percent of the bank surface.

Sediment Resuspension During Storms Documented by Sediment Trap Experiments

Long-term deployments of sediment traps in the New England region have documented the resuspension of seabed sediment during storms. Grain-size analyses of samples collected from September 1978 to March 1979 (table 2) in a trap 3 m above the seabed in a water depth of 62 m on Georges Bank (a part of the New England continental shelf, not shown in fig. 1) documented the resuspension of grains constituting clay, silt, and the sand grades of 4 phi, 3 phi, and a trace of 2 phi (Parmenter and others, 1983).

A second trap deployed in the same area a year later, from December 1979 to May 1980, 3 m above the seabed in a water depth of 64 m (table 3), recorded a similar suite of sediment grades, and 2-phi sand was present in small amounts (Moody and others, 1987). During this deployment, pressure and current speeds were recorded 1 m above the seabed and were used to calculate seabed stress which showed that maximum values for eight storms ranged from ~22 to 60 dynes per square centimeter (~2.2 to 6 Pa; Moody and others, 1987, fig. 5).

Closer to the Massachusetts coast, off Boston (fig. 1), a sediment trap was deployed on a subsurface mooring 3.7 m above the seabed in 32 m water depth from December 1989 to February 1990. This trap was located in Massachusetts Bay between Stellwagen Bank and the coast in a water depth similar to that of the bank crest. During this period, a series of samples was collected, each representing an 8.5-day interval (table 4). The samples recorded the resuspension of clay, silt, 3- and 4-phi sand, and small amounts of 2-phi sand during storms (Reid and others, 2005).

Table 2. Grain-size analyses of suspended sediment collected on Georges Bank in 1978–79.

[Location: site K, southeastern flank of Georges Bank (41.037 N., -67.558 W.). Sediment trap on tripod deployed for 161 days from September 30, 1978, to March 10, 1979. Water depth 62 meters. Instrument height 3 meters above seabed. Sample numbers represent descending sediment intervals (not depths) analyzed over a vertical depth of 0–8 centimeters in the sample collected by the sediment trap. Phi grade values interpreted from cumulative weight percent curves of Parmenter and others (1983, fig. 3). Weight percent values may not add to 100 due to rounding. See Moody and others (1987, fig. 3) for map showing location of site K. t, trace = approximately less than 3 weight percent; ~, approximately]

Sample number	Weight percent, phi grades						
	Sand					Silt	Clay
	0	1	2	3	4	5 to 8	9 to 11
1	0.0	0.0	t	61	24	5	~7
2	0.0	0.0	t	29	16	23	~29
3 and 4	0.0	0.0	t	29	20	20	~28
5	0.0	0.0	t	30	23	21	~23
6	0.0	0.0	t	12	18	33	~35
7	0.0	0.0	t	57	12	11	~17

Table 3. Grain-size analyses of suspended sediment collected on Georges Bank in 1979–80.

[Location: site K, southeastern flank of Georges Bank (41.039 N., -67.557 W). Sediment trap number ST001 on tripod deployed for 165 days from December 15, 1979, to May 28, 1980. Water depth 64 meters. Instrument height 3 meters above seabed. Thirteen individual samples represent 5- to 10-centimeter (cm) intervals of a 105-cm vertical sediment sample collected by the sediment trap. See Bothner and others (1985), Moody and others (1987), and usSEABED database (Reid and others, 2005). Note: Water depth and position are from usSeabed database. Deployment dates are from Moody and others (1987). See Moody and others (1987, fig. 3) for map showing location of site K. DB_ID, grain-size analysis number for sample in usSEABED database]

DB_ID	Weight percent, phi grades						
	Sand					Silt	Clay
	0	1	2	3	4	5 to 8	9 to 11
AB100	0.0	0.0	1.7	7.8	8.6	63.1	19.0
AB101	0.0	0.0	2.6	16.4	18.0	46.3	16.7
AB102	0.0	0.0	4.7	2.8	4.6	58.4	29.6
AB103	0.0	0.0	0.9	0.5	1.2	81.9	15.5
AB104	0.0	0.0	0.5	3.0	2.4	70.9	23.2
AB105	0.0	0.0	0.7	4.6	6.4	71.6	16.7
AB106	0.0	0.0	2.0	7.8	12.0	64.5	13.7
AB107	0.0	0.0	0.8	14.4	29.8	44.6	10.4
AB108	0.0	0.0	2.1	28.0	22.0	34.4	13.4
AB109	0.0	0.0	2.1	26.3	24.4	37.3	15.9
AB110	0.0	0.0	1.4	13.5	17.7	48.7	18.6
AB111	0.0	0.0	1.3	32.5	21.4	35.9	8.9
AB112	0.0	0.0	1.3	32.5	21.4	35.9	8.9

Table 4. Grain-size analyses of suspended sediment collected in Massachusetts Bay in 1989–90.

[Location: site LT–A, Massachusetts Bay (42.377 N., -70.783 W.). Water depth 32 meters. Time-series sediment trap number W1 on subsurface mooring. Instrument height 3.7 meters above seabed. Each of six samples represents an 8.5-day interval from December 14, 1989, to February 12, 1990; only grains less than 1-millimeter diameter were analyzed (Bothner, unpub. data, 1990). Grain-size data from one sample in this series were not included because sample size was very small. See usSEABED database (Reid and others, 2005). See Bothner and others (2007) for map showing location of site LT–A. DB_ID, grain-size analysis number for sample in usSEABED database; nd, no data]

DB_ID	Weight percent, phi grades						
	Sand					Silt	Clay
	0	1	2	3	4	5 to 8	9 to 11
AH099	nd	0.0	0.3	1.6	3.4	48.8	45.9
AH100	nd	0.0	0.6	2.1	3.5	48.6	45.3
AH101	nd	0.0	0.7	2.4	3.1	49.9	44.0
AH103	nd	0.0	1.1	3.4	3.3	52.0	40.3
AH104	nd	0.0	3.6	1.7	3.7	54.2	36.9
AH105	nd	0.0	1.8	3.0	5.8	46.2	43.2

Data Types and Collection Methods

The characterization and identification of seabed substrates requires the integration of areal geophysical data provided by multibeam sonar backscatter and bathymetric imagery of the seabed with groundtruth data provided by local video and photographic imagery and grain-size analyses of sediment samples. A bathymetric and backscatter survey of the Stellwagen Bank National Marine Sanctuary region (~3,780 km^2) was conducted using a Simrad EM1000 multibeam echosounder during 1994–6 in collaboration with the Canadian Hydrographic Service and the University of New Brunswick, Canada. The survey region was subdivided into 18 quadrangles (fig. 1), and several series of maps showing seabed topography, sun-illuminated topographic imagery, backscatter reflectivity, and ruggedness have been published, along with descriptions of survey and data processing methods (Valentine, 2005; Valentine and others, 1998). Multibeam sonar data used in the present study are from quadrangle 6 (211 km^2), a bank and basin terrain lying in water depths ranging from 30 to 185 m. Sediment grain-size analyses (325 stations) and video and photographic imagery (288 stations) were acquired in 1993–6, 1998, 1999, 2003, and 2004 and used to interpret the features and seabed patterns observed in the sonar imagery (Valentine and Gallea, 2015). There have not been any multibeam sonar surveys since 1994–6, but video and photographic imagery and sediment samples collected into 2004 show that the substrate types described here did not change.

As part of the process of mapping the sea floor, the U.S. Geological Survey (USGS) developed the SEABed Observation and Sampling System (SEABOSS) equipped with a grab sampler and cameras to collect sediment samples and video and photographic images of the seabed to aid in the interpretation of the sonar imagery (Valentine and others, 2000; Valentine and Gallea, 2015). The SEABOSS has a Van Veen sediment grab sampler mounted in the center of a frame that ensures the sampler is properly oriented on the seabed when a sample is collected. The upper 2 cm of sediment, representing the surface of the seabed, were removed from the sample with a rectangular shovel 2 cm deep and stored in a plastic bag for grain-size analysis that was performed at the USGS Woods Hole Coastal and Marine Science Center in Woods Hole, Mass., using a standard suite of analytical methods (Poppe and others, 2005). This laboratory has been in operation since 1963 and has analyzed many thousands of sediment samples collected by the USGS in New England.

Results

New, Simplified Classification of Sediment Grains by Size, Transport Mode, and Ecological Significance—Composite Grades

As described in the section "Classification of Sediment Grains by Size—Grades and Aggregates," sediment grains historically have been classified into grades by grain size, with the range of grain diameters doubling for each coarser grade (fig. 2). This is accepted practice and provides a valuable standard that makes the results of grain-size analyses comparable. It is the foundation from which new approaches to sediment classification can evolve. In this study, the mapping of geologic substrates is improved by re-classifying sediment grades into groups of grades referred to as "composite grades" (fig. 2; table 1) that are based not only on their grain-size content, but also on their mode of transport and ecological role.

Five composite grades that are identified by quantitative grain-size analysis are mud (silt and clay; 5 to 11 phi), fine-grained sand (3 and 4 phi), coarse-grained sand (0, 1, and 2 phi), $gravel_1$ (−1 and −2 phi), and $gravel_2$ (−3, −4, and −5 phi). Three composite grades that are identified by qualitative visual analysis of seabed imagery are pebble gravel, including granules (−1 to −5 phi), cobble gravel (−6 and −7 phi), and boulder gravel (−8 to −11 phi).

Clay and Silt Aggregates Combined Into a Mud Composite Grade

Clay and silt grains consist of seven sediment grades (5 to 11 phi) whose maximum grain size is <0.062 mm (fig. 2). These grades were combined by Folk (1954) into a composite mud aggregate that simplified the classification of very small sedimentary particles. This study follows Folk; mud is treated as a composite grade consisting of clay and silt aggregates. Mud-size particles characteristically travel in suspension and are transported farther than larger grains, and they are deposited in the basins, the least energetic parts of the mapped region (Warner and others, 2008, fig. 13). The concept of "mud" is familiar to biologists and implies the occupancy of certain faunal types and the probable presence of burrows.

Simplification of the Traditional Five-Grade Sand Classification Into Two Composite Grades—Fine-Grained Sand and Coarse-Grained Sand

The 1994–6 multibeam echosounder survey of the central part of Stellwagen Bank revealed seabed structures (the leading edges of rippled sand sheets) whose morphology indicated movement of sediment westward from the bank's gently sloping eastern flank onto its more steeply sloping western flank and into the deeper waters of Stellwagen Basin (Valentine, 2005, map B; Valentine, 2012; Valentine and others, 2010, quadrangle 5).

In the early stages of substrate characterization and identification in this study, it became apparent that the weight percents of individual sediment grades in a sample were related to water depth. As was expected, the mud grades (>4 phi) were almost absent on the bank and most abundant in the deep water of the basins. Unexpectedly, the five sand grades were observed to segregate into two groups, with coarse phi grades (0, 1, and 2) being most abundant in samples at water depths <50 m on the bank, and fine phi grades (3 and 4) being most abundant between ~50 and ~90 m on the western flank of the bank. This observation suggests that these two sand groups represent different modes of transport, with 0-, 1-, and 2-phi sand being a lag deposit or moving as bedload, and 3- and 4-phi sand moving in suspension. This natural segregation of grades by grain size can be used to classify naturally occurring sediments and to characterize and identify substrates.

Plots of the grain-size distribution of 41 samples along transect A that extends from east to west across Stellwagen Bank into Stellwagen Basin (figs. 1 and 4) show an uneven distribution of individual phi grades related to water depth (see Valentine and others, 2010, for grain-size analysis data). At water depths shallower than ~50 m, the rippled bank surface is primarily coarse sediment (0, 1, 2 phi) and contains little fine sediment (3 phi, 4 phi, mud). At water depths between ~50 and ~90 m on the western flank, the unrippled seabed is dominantly 3-phi sand (~30 to ~55 percent) and 4-phi sand (~25 to ~50 percent). Mud, which is all but absent on shallower parts of the bank, increases to ~5 to ~25 percent in this depth interval. Below ~90 m, in the basin, mud is dominant (>90 weight percent) and all other phi grades are <1 percent, except for 4-phi sand which is <4 percent.

The formation of these texturally distinctive sediment deposits supports the interpretation that coarse sediment (0, 1, 2 phi) is stationary and (or) moves as bedload on the bank at water depths <~50 m; that fine sediment (3 phi, 4 phi, mud) is resuspended by wave-orbital storm currents in shallow parts of the bank and, aided by tidal and wind-driven currents, travels in suspension to the western flank (~50 to ~90 m) where it settles onto the seabed; and that most mud grains travel farther in suspension and settle in Stellwagen Basin at depths >90 m. The distribution of 2-phi sand (fig. 4*B*) indicates that a small amount of it is resuspended and settles onto the western flank.

These observations, and the results of the sediment transport studies described in the section "Sediment Transport Processes and the Movement of Sediment Grains in the Region" (especially the sediment trap experiments that documented the resuspension of mud and 3- and 4- phi sand to at least 3 m above the seabed during storms), led to a reclassification of the five sand grades on the basis of their modes of transport for the purpose of mapping substrates. Here, the grades (3 and 4 phi) that are resuspended and move in suspension are combined into a composite grade of "fine-grained sand," and the grades (0, 1, and 2 phi) that remain on the seabed are combined into a composite grade of "coarse-grained sand" (fig. 2). The proportions of each of the composite sand grades in a sample or substrate provide information on the modes of transport of the grains found in the sediment and on the kinds of organisms that can inhabit it.

Combining the traditional five sand grades into two composite grades is a key to the characterization, identification, and mapping of substrate types presented here. The observation that fine-grained sand and coarse-grained sand move as described likely applies to any region where currents related to storms and tides resuspend and transport sediment. Exceptions likely are surf zones and areas that experience exceptionally strong tidal currents.

Gravel Classified into Composite Grades by Grain-Size Analysis and by Analysis of Seabed Imagery

The Van Veen sediment grab sampler used for collecting sediment samples in the Stellwagen Bank region rarely successfully collects gravel grains larger than pebbles (≥64-mm grain diameter). Therefore, a determination of the distribution of gravel in substrates requires two approaches, an evaluation of granule and pebble content (2 to <64 mm) by quantitative grain-size analysis of collected samples, where possible, and by a qualitative evaluation of the presence of pebbles, cobbles, and boulders through visual interpretation of seabed video and photographic imagery.

In this study, gravel grains between 2 and <64 mm in diameter (−1 to −5 phi) that can be sampled and then quantified by grain-size analysis are combined into two composite grades, gravel_1 and gravel_2 (fig. 2). This simplifies the characterization of these relatively small gravel grains without obscuring their possible ecological role as sites of biological attachment. The granule and fine pebble grades (−1 and −2 phi) are combined into composite grade gravel_1 in which the largest grains are less than a centimeter (cm) in diameter. The smallest of these grades (granules, 2 to <4 mm) are only twice as large as very coarse sand, and it is likely that they and fine pebble gravel (4 to <8 mm) behave somewhat like sand grains insofar as they are unsuitable for the attachment of organisms. The three larger pebble grades (−3 to −5 phi) are combined into composite grade gravel_2 that has a grain-diameter range of 8 to <64 mm, which is more likely to provide surface area suitable for attachment of organisms and conforms closely to the concept of gravel held by many nongeologists.

In general, the occurrence of the gravel grades and their potential ecological role in forming substrates can best be determined by an analysis of video and photographic imagery. This applies to the pebble gravel (2 to <64 mm) composite grade if it cannot be sampled and to the cobble gravel (64 to <256 mm) and boulder gravel (≥256 mm) composite grades. The pebble gravel composite grade includes granules and four pebble grades and is equivalent in grain size to combined

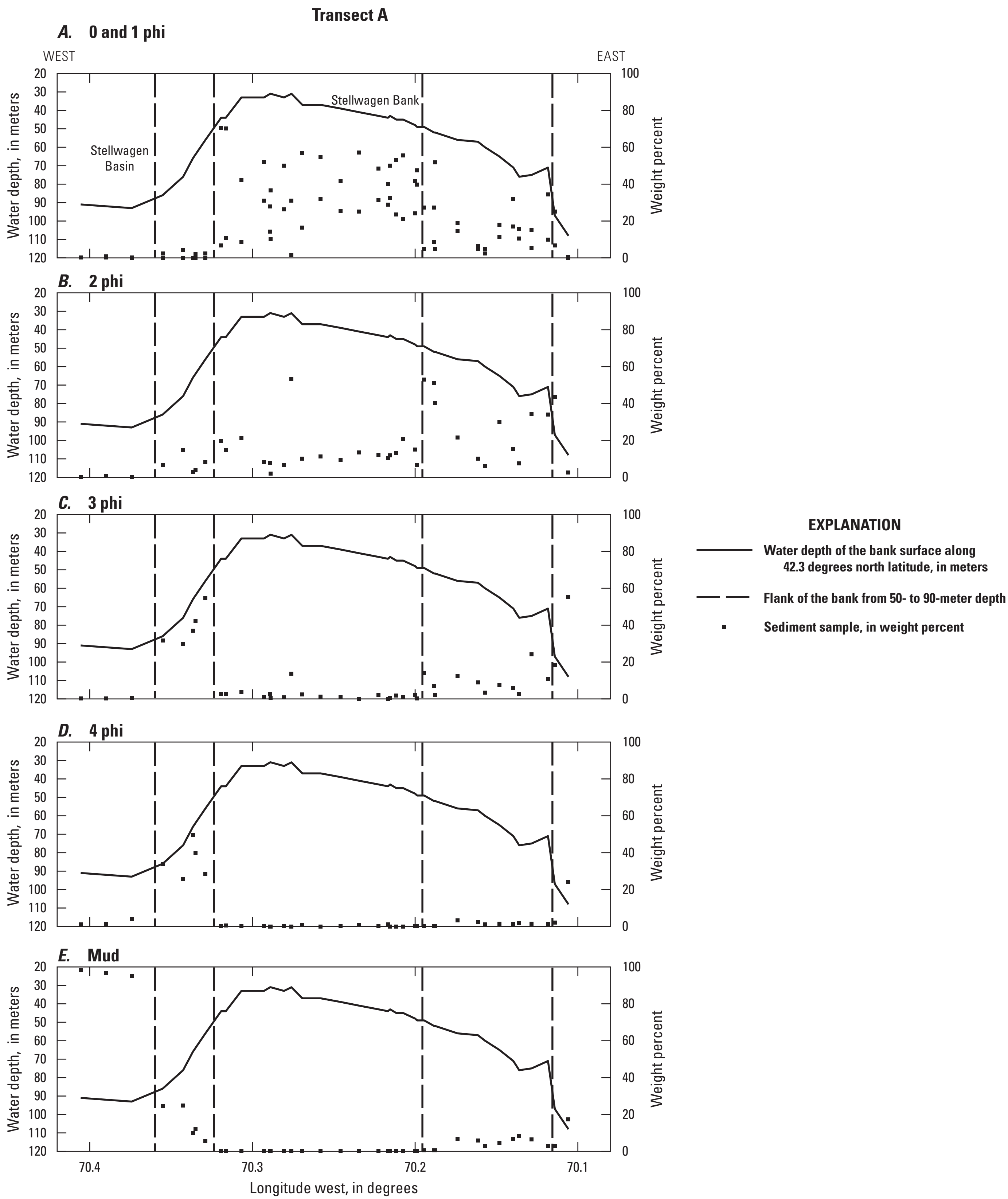


Figure 4. Cross sections of transect A, east-west, across Stellwagen Bank and into Stellwagen Basin with locations of sediment samples and the distribution of phi grain sizes relative to topography. *A*, 0 and 1 phi; *B*, 2 phi; *C*, 3 phi; *D*, 4 phi; and *E*, mud. Storm-wave currents from the northeast and east-west tidal currents resuspend and transport fine sediments from the bank onto the western flank and into Stellwagen Basin. Fine-grained sand (3 and 4 phi) and mud are deposited on the western flank.

$gravel_1$ and $gravel_2$ (fig. 2). The composite cobble gravel and boulder gravel grades in this study are equivalent to the composite cobble and boulder gravel grades of Wentworth (1922).

New Classification of Naturally Occurring Sediments—Sediment Classes

As classification is the process of arranging things into groups based on their properties, it follows that the more properties the things have, the more complex the classification will be. Sediment grains are classified by the increasing ranges of grain diameters into the grades of Udden (1914). Sediment grades are classified by combining them into the aggregates of Wentworth (1922) and Folk (1954). Naturally occurring sediments are classified by the weight percent content of their aggregates based on grain-size analysis (see section "Classification of Naturally Occurring Sediments—Sediment Classes") to produce a more complex classification, the sediment classes of Wentworth (1922) and Folk (1954). Here, sediments are classified by the weight percent content of their aggregates and composite grades (figs. 2 and 5; table 1).

The new sediment classification is intended to improve the mapping of geologic substrates and to provide information on the potential ecological use of the substrates by organisms by (1) simplifying the properties of sediment classes by using newly defined composite grades for sand and gravel; (2) placing less emphasis than Folk (1954) on gravel content; (3) providing information on the mode of transport of the sand component (for example, fine-grained sand moves in suspension and coarse-grained sand is stationary or moves as bedload); and (4) relying on video and photographic imagery to identify pebble, cobble, and boulder gravel.

In this classification of naturally occurring sediments, 20 basic sediment classes are defined by their aggregate (mud, sand, gravel) content based on grain-size analysis (fig. 5). Thirteen sediment classes have mud or sand or gravel content ≥50 weight percent (tables 5 and 6, in back of report). Seven classes of "mixed" sediment have mud, sand, and gravel content each <50 weight percent (table 7, in back of report). The lower limit for mud and sand to be included in a class is ≥10 weight percent of the sediment and for gravel ≥25 weight percent. The higher threshold for gravel assumes that sediment collected with a grab sampler that contains <25 percent gravel will likely contain gravel grains that are too small (<64 mm diameter) and too sparse to be used by species for attachment or other purposes. The 20 basic sediment classes of this classification increase to 82 when they are modified by incorporating the weight percent of the composite grades fine- and coarse-grained sand they contain (tables 5–7, in back of report). The number of classes would also increase if the gravel content of composite grades $gravel_1$ and $gravel_2$ were to

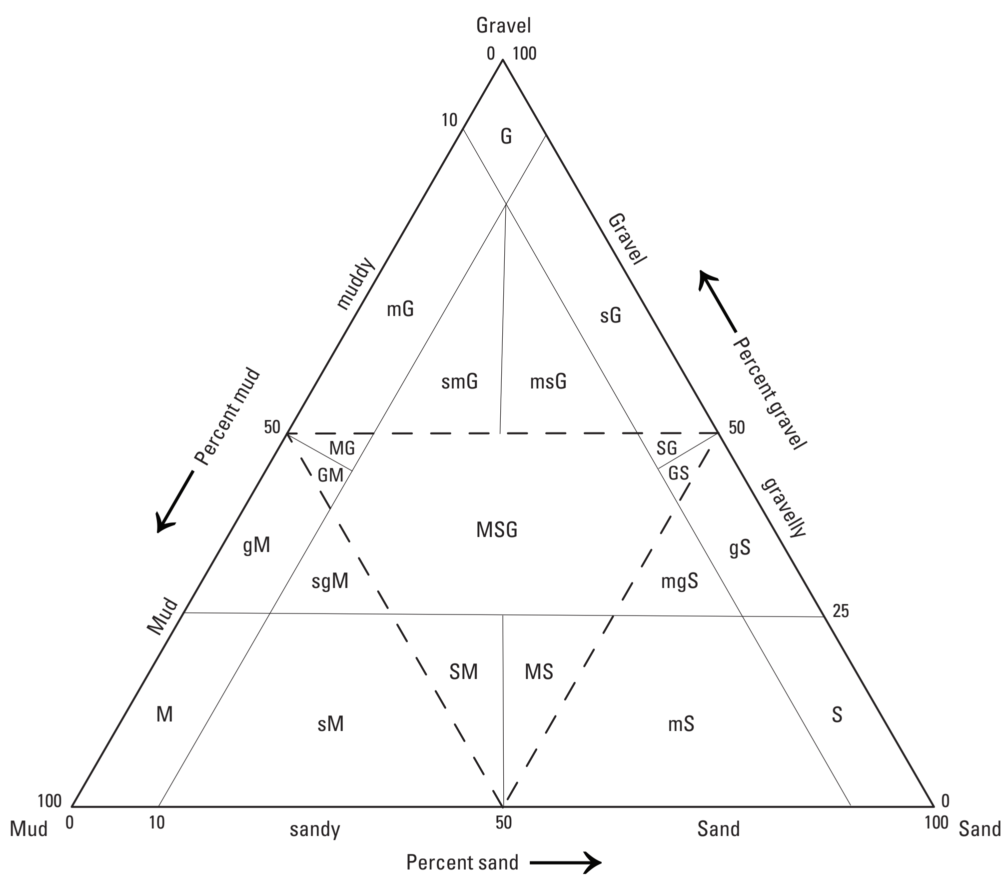


Figure 5. Ternary diagram showing grain-size composition of 20 classes of naturally occurring sediments defined in this study based on weight percent of their aggregates (mud, sand, and gravel) content as determined by grain-size analysis. The threshold for recognition of mud or sand in a class is 10 weight percent and for gravel 25 percent. Outside the dashed line, 13 basic sediment classes are mud or sand or gravel. Inside the dashed line, 7 sediment classes are mixed mud and sand and gravel, but note that MSG represents one of six possible combinations of mud, sand, and gravel. See tables 6 and 7 for descriptions of the properties of sediment classes. M, mud; m, muddy; S, sand; s, sandy; G, gravel; g, gravelly.

be included, but it would unnecessarily increase the complexity of class names. The $gravel_1$ and $gravel_2$ content can be better shown in tables that list substrate sediment composition (table 8, in back of report). The name of the sediment class (for example, muddy, gravelly, coarse-grained sand; mgcgS) that is an element of a substrate is indicated in a substrate's name (see section "Substrate Symbols and Names" below).

Gravel and nonsediments such as rock, shell, or semiconsolidated mud that cannot be sampled constitute classes that are identified by visual analysis of seabed imagery (table 9, in back of report). No guidelines are provided here for estimating and classifying the areal extent of gravel and nonsediments.

Substrates are Characterized and Identified, Not Classified

In this study, substrates are not classified; they are characterized and identified based on their observed properties (their standard descriptors), which include grain-size composition (the sediment class described above), distribution of grain diameters, nonsediments (for example, rock outcrops), substrate mobility, substrate layering, seabed structures, and water depth (where defining). If substrates were to be classified, it would be necessary to classify each of the standard descriptors, which would produce a very large number of substrate classes and a complicated classification that likely would find little use.

Substrate Grain-Size Composition

The grain-size composition of a substrate, represented by its sediment class, is determined by grain-size analyses of sediment samples collected from the substrate and from analysis of video and photographic imagery of the seabed where samples cannot be collected. The number of possible identifiable substrates depends on the number of sediment classes that are recognized by the sediment classification scheme. Fewer substrates will be identifiable if the sediment classification recognizes few sediment classes.

For a substrate that can be sampled, its grain-size composition is defined by the mean weight percent of each of the two aggregates (sand, gravel) and five composite grades (mud, fine-grained sand, coarse-grained sand, $gravel_1$, $gravel_2$) it possibly contains (fig. 2; table 8, columns 7–13, in back of report). Mud, sand, and gravel are listed in the sediment class name in order of increasing weight percent.

For a substrate that cannot be sampled and must be analyzed using seabed imagery, its grain-size composition is defined by the presence of three composite grades of pebble gravel, cobble gravel, and boulder gravel it possibly contains (fig. 2) or by the presence of nonsediments, such as rock outcrop, shell deposit, and semiconsolidated mud. The terms pebble, cobble, and boulder in the class name indicate presence only; they are not listed in order of increasing areal coverage.

Distribution of Grain Diameters in a Sediment

A sediment can be characterized by the distribution of grain diameters that constitute most of its particles. "Sorting" is a measure of the uniformity of the distribution of grain diameters in a sediment, and the degree of sorting can be expressed in phi units and in millimeters. It has been used to interpret the processes that caused the particles to occur together (Folk and Ward, 1957). For marine sediments, a mud with a history of suspended transport will have a distribution of grain diameters different from a sand that has a long history of transport from its source area or a muddy gravelly sand that has a short history of deposition and little transport from a source of mixed sediment (for example, a melting tidewater glacier).

Measuring the Uniformity of the Distribution of Grain Diameters in a Sediment

Consider a sediment in which the phi grain diameters are assumed to have a normal distribution about the mean grain size. A statistical measure of sorting called the "phi deviation measure" developed by Inman (1952, table 1) and called the "graphic standard deviation" by Folk (1980, p. 42) uses the phi values that represent 16 and 84 percent on a sample's cumulative weight percent curve to determine the number of phi units that lie in the central 68 percent of the grain-size distribution (±1 standard deviation about the mean) and divides this value by two $[(\varphi 84 - \varphi 16) / 2]$ to determine the standard deviation in phi units, which is the measure of sorting. Another sorting measure, the "inclusive graphic standard deviation" developed by Folk and Ward (1957) is the average of the standard deviations calculated from the central 68 percent and the central 90 percent of the grain-size distribution $[(\varphi 84 - \varphi 16) / 4 + (\varphi 95 - \varphi 5) / 6.6]$. For these measures of grain uniformity, the smaller the standard deviation in phi units, the better sorted is the sediment (Folk and Ward, 1957, p. 13).

Sorting values expressed in phi units warrant careful interpretation. Each grade of the Krumbein (1936) grain-diameter classification (based on equal phi intervals) represents a grade of the Udden (1914) grain-diameter classification (based on unequal millimeter intervals; fig. 2). In Udden's classification, the grain-diameter range in millimeters doubles for each coarser sediment grade. The result is that the individual sand grades of Udden have a much greater grain-diameter spread (in millimeters) than the individual mud grades. The standard deviation of a sand sample expressed in phi units can represent fewer phi grades than the standard deviation of a mud sample and thus be considered better sorted than the mud. However, the few phi grades of the sand can represent a wider spread of grain diameters expressed in millimeters than the many phi grades of the mud. Krumbein (1936) emphasized that the standard deviation of the grain-size distribution of a sediment expressed in phi units measures the spread of grain diameters about the mean and is a measure of sorting "… at least in a descriptive sense."

It is informative to compare the standard deviation about the mean of a variety of sediment types based on published sediment cumulative weight percent curves using the phi deviation measure of Inman (1952; referred to in this report as the phi standard deviation). A comparison of two sand samples (Inman, 1952, figs. 4 and 5, table 3a) shows that a coarse-grained sand (sample 3) has a phi standard deviation of 0.50 phi, a phi mean diameter of 0.26 phi (0.84 mm), and a maximum difference in grain diameters of 0.59 mm (in the interval ±1 standard deviation about the mean); while a fine-grained sand (sample 12) has a similar standard deviation of 0.51 phi, but a smaller mean diameter of 2.10 phi (0.23 mm) and a much smaller maximum difference in grain diameters of 0.17 mm. Thus, these two samples are similarly sorted as measured by the phi standard deviation, but sample 12 is better sorted based on the maximum differences in grain diameters (in millimeters, ±1 standard deviation) of the samples.

Another comparison of Inman's samples shows that a fine-grained sand (sample 60) has a phi standard deviation of 0.41 phi, a phi mean diameter of 3.24 phi (0.11 mm), and a maximum difference in grain diameters of 0.06 mm; while a muddy fine-grained sand (sample 34) has a larger standard deviation of 0.74 phi, a smaller mean of 4.06 phi (0.06 mm), and a maximum difference in grain diameters of 0.06 mm. Thus, these two samples differ in phi standard deviation, and sample 60 would be considered the best sorted because it has the smallest standard deviation, but they are similarly sorted if the maximum difference in grain diameters (in millimeters, ±1 standard deviation) is the measure.

A published cumulative weight percent curve for a core sample of mud (Alonso and others, 1996, fig. 6, 897C–26R–02, 29–31 cm) was analyzed using Inman's (1952) phi measures of mean and standard deviation. The sample has a large phi standard deviation of 2 phi, a phi mean diameter of 8.8 phi (0.002 mm), and a maximum difference in grain diameters of 0.008 mm. This mud would be considered very poorly sorted because its phi standard deviation is large, but it is very uniform in grain size if the maximum difference in grain diameters (in millimeters, ±1 standard deviation) is the measure.

Another measure of grain-size uniformity (sorting) in a sediment is the distribution of grain diameters measured in millimeters. Trask (1930, p. 594) developed a dimensionless measure to determine the uniformity of sediment grain-size distribution in a sample by using the millimeter values that represent 25 and 75 percent on the sample's cumulative weight percent curve. Folk (1966, p. 82) recommended against using Trask's measure because it is based only on the central 50 percent of a sample's grain-size distribution.

In this study, the uniformity of the distribution of grain diameters in a sediment is approximated by using a new method that simply calculates the cumulative range, and the maximum difference in size, of grain diameters (in millimeters), represented by every phi grade that constitutes ≥10 weight percent of a sample or substrate. These phi grades are considered significant and together can constitute more than 60 to 100 percent of the substrate (table 8, in back of report). For example, in a mud, if the significant phi grades are 5, 6, 7, 8, and 9, the grain diameters of that portion of the sample or substrate can range from 0.002 to <0.062 mm, a maximum difference of ~0.060 mm. In a sand, if the significant phi grades are 2, 1, and 0, the grain diameters can range from 0.25 to <2.00 mm, a maximum difference of ~1.750 mm.

Using this method, the grains in the mud (which represent five significant phi grades) are shown to be more uniform in size than the grains in the sand (which represent three significant phi grades). A user can redefine the ≥10 weight percent threshold, if desired. For some samples and substrates with appreciable portions of clay and silt, the total mud content can be much greater than 10 percent even though individual clay and silt phi grades are all <10 percent. In this case, the clay and silt phi grades can be combined into a composite mud grade if their cumulative weight percent is ≥10, which is the approach followed in table 8, in back of report (substrates D2, G1, G2). Note that the grain-diameter difference by itself does not always accurately represent the fabric of the sediment. For example, substrates G1 and G2 have identical grain-size ranges (>0 to <0.250 mm) and maximum grain-size differences (~0.250 mm), but G2 is finer grained as it contains more mud and 4-phi sand than G1.

Small differences in grain size can be responsible for large differences in the physical properties of sediments. For example, a muddy fine-grained sand (G1) with grain diameters that range from >0 to <0.250 mm (maximum difference ~0.250 mm) is more suitable for constructing burrows than a coarse-grained sand (A1) with grain diameters that range from 0.25 to <2 mm (maximum difference ~1.75 mm) that is more suitable for hosting infaunal species that require oxygenated water in the sediment. To many biologists, the degree of sorting of a substrate expressed as a statistical measure in phi units may have little ecological meaning. However, knowing the range of grain diameters in a substrate in millimeters, and which grades are dominant, could provide information about the substrate preferences of species with regard to burrowing, food gathering, attachment, and selection of spawning sites, among others.

Substrate Mobility, Layering, and Structures

Substrate mobility, layering, and structures must be determined by analysis of seabed imagery (fig. 6; tables 9 and 10, in back of report). Substrate mobility (or immobility) is recognized by the presence (or absence) of sediment ripples observed in seabed imagery. Sediment movement affects the grain-size range of substrates and the presence or absence of benthic species and seabed structures such as burrows (fig. 6*N*, in back of report). The shape of bedforms provides information on the direction of sediment transport and the mechanisms driving it. For example, in the Stellwagen Bank region, large bedforms generally are symmetrical in cross section with their crests oriented northwest-southeast, indicating they are formed by the wave-orbital currents that are generated by storm waves arriving from the northeast quadrant (fig. 6*A* and *B,* in back of report). In layered substrates, an upper mobile substrate layer can be an ephemeral or increasingly permanent veneer that partially covers a lower substrate and affects seabed usage by organisms that burrow into or attach to the seabed (fig. 6*I* and *J,* in back of report). The presence or absence of mobile sediment is indicated in a substrate's name (see section "Substrate Symbols and Names").

Layering of substrates can be in the form of a thin layer of coarse-grained sand that partially veneers underlying gravel, or surrounds cobbles and boulders in shallow water, or partially covers a clay deposit, or of muddy fine-grained sand that drapes and partially covers gravel in deep water (fig. 6*I*–*P*, in back of report). In layered substrates, each layer is considered a substrate. A layered substrate usually is not detectable in samples collected unaccompanied by video imagery, as the layers can be mixed during the act of sampling. Sometimes the upper substrate alone can be sampled with the aid of real-time seabed observation. Layered substrates can occur in both dynamic and quiescent environments. These substrates document processes of erosion, transport, and deposition and can be evidence of changing conditions on the seabed that can have ecological implications for benthic fish and invertebrates. The presence of layering is indicated in a substrate's name (see section "Substrate Symbols and Names").

Regional topographic features observed in multibeam sonar imagery, such as banks and basins, can predict substrate character. As obvious examples, shallow banks likely will be sites of sediment movement and coarse substrates, whereas basins likely will be sites of deposition and fine substrates. Local geologic structures, as observed in video imagery, serve to increase the surficial complexity of substrates and provide information on possible seabed usage by benthic species. Structures, such as ripples and dunes, create a patterned surface on the seabed, are evidence of currents, and can move over other substrates and potentially smother attached organisms. Boulder ridges and rock outcrops, often with voids, provide substrate for attachment of some organisms and for refuge for others, as do shell deposits, gravel pavements, and gravel lag deposits in ripple and dune troughs. Biogenic structures include burrows, depressions, and mounds. Fish and crab burrows indicate the presence of those species and a substrate that contains enough mud to provide the strength required to support burrows. Biologic structures, such as attached and emergent epifauna, also contribute to seabed complexity.

Substrate Mapping

The mapping methods described here were used to compile a series of seabed maps in quadrangle 6 of the Stellwagen Bank region (fig. 1) showing the distribution of geologic substrates. Related thematic maps show substrate mobility, and sand and mud content; and supporting maps show the distribution of seabed topography, ruggedness, and sonar backscatter intensity. See Valentine and Gallea (2015) for the quadrangle 6 map sheets, digital files, and supporting data.

Topographic Features, Ruggedness, and Sonar Backscatter Intensity of the Seabed

Seabed topography is depicted by a mix of 1-m and 5-m bathymetric contours overlain on sun-illuminated topographic imagery. In the Stellwagen Bank region, most topographic features are accurately represented by 5-m contours (Valentine and Gallea, 2015, map A). However, 5-m contours do not adequately show relief in areas where they are widely spaced on a gently sloping seabed that is characterized by gravel deposits, boulder ridges, long-wavelength bedforms, seabed hummocks, and the leading edges of sand sheets. In such areas on the map, the 5-m contours are supplemented by 1-m contours to display these complex, low-relief topographic features. In areas where 5-m contours are widely spaced on relatively featureless seabed, the 1-m contours are not shown because minor changes in water depths recorded by the sonar are not resolvable to the extent that they can be contoured at a 1-m interval and produce usable information. Such contours produce incoherent patterns of lines that misrepresent topographic complexity.

Bathymetric data also are used for seabed ruggedness analysis, which characterizes seabed topography by measuring changes in elevation (water depth) over small areas (Valentine and Gallea, 2015, map B). Ruggedness analysis is useful for delineating steep features, such as bank slopes, and subtle features observed in relatively smooth areas where elevation changes are small. Seabed ruggedness analysis is based on a terrain ruggedness index (TRI) developed by Riley and others (1999) to quantify topographic heterogeneity on land. The TRI of Riley and others measures the sum change in elevation between a central grid cell (pixel) and its eight neighboring grid cells, found by squaring the eight differences in elevation, summing the squared differences, and taking the square root of the sum. Here, a seabed TRI measures ruggedness more directly by calculating the average change in elevation between a central pixel and its eight neighbors, found by averaging the absolute values of the eight differences in elevation. Comparing the two methods using a simple example, a central pixel (representing a positive feature) with an elevation (water depth) value of 10 m and eight neighboring pixels with values of 15 m would have a TRI value of 14.1 m using the method of Riley and others (1999) and a seabed TRI value of 5.0 m using the method employed here.

Sonar backscatter intensity values are a measure of seabed hardness. Patterns of backscatter intensity can assist in determining the boundaries of substrates, particularly where large changes in intensity occur over short distances (compare figs. 7 and 8; Valentine and Gallea, 2015, maps C and D). In quadrangle 6, backscatter intensity strongly delineates the coarse-grained sand and gravel that covers the tops and upper slopes (substrates D2 and F) of the Ninety Meter Banks from the fine-grained sand and mud on the lower bank slopes and in the bounding valleys (substrates G1 and G2). Backscatter values also assist in delineating the more muddy substrate G2 from the less muddy G1. Other substrates are less well defined geographically by backscatter values. These include the rippled, coarse-grained sand of substrate A1, the coarse-grained sand and gravel of substrate D1, and the rippled, coarse-grained sand on gravel of substrate B. The backscatter values of substrate E, a uniform coarse-grained sand, range from relatively low in smooth areas to relatively high where topographic features are present. Seabed backscatter patterns observed in this data alone do not accurately represent the distribution of many of the mapped geologic substrates, underscoring the importance of using sediment sampling and video and photographic imagery to characterize and identify them.

Presenting the Properties of Geologic Substrates

A mapped geologic substrate represents a collection of samples and observations that share similar properties (fig. 8). Some properties are present or absent (for example, substrates are rippled or not, layered or not). The sediment content of a substrate (as determined by grain-size analysis) is represented by seven aggregates and composite grades (mud, fine-grained sand, coarse-grained sand, sand, $gravel_1$, $gravel_2$, and gravel). Each of these is expressed as the mean of the defining samples of a substrate (table 8, in back of report). The properties of each substrate are presented in three levels of detail: (1) a short description provided by the substrate name (see section “Substrate Symbols and Names”); (2) a table showing a summary of its physical properties, including sediment grain-size content, grain-diameter distribution and maximum grain-size differences, presence of nonsediments, substrate mobility, layering, and water-depth range (table 8, in back of report); and (3) a detailed text description of its physical properties and its relation to adjacent substrates (Valentine and Gallea, 2015). In addition, a table showing the results of the original grain-size analyses in phi grades is an important source for users who want to see the grain content of all samples (Valentine and Gallea, 2015, table 4).

Depicting Boundaries of Mapped Substrates

The quality of substrate identification and mapping depends on the density of samples and observations available to interpret multibeam sonar imagery. Fewer samples are required to identify substrate boundaries where they align with topographic features and sonar backscatter patterns. Substrate distribution can be shown on maps using three methods that are based on the density of data. First, substrates are mapped as natural (irregular-sided) polygons if the density of data allows the interpretation of boundaries with confidence (fig. 8). These substrates are represented by colored polygons that have no drawn boundaries because a line indicates a degree of certainty that usually is not warranted in substrate mapping.

Second, where transitions between substrates are ambiguous because of the low number of samples, substrates are mapped as provisional (straight-sided) polygons with no drawn boundaries in order to approximate the geographic extent of the substrates and to alert the user that there is uncertainty in the placement of their boundaries. Third, symbols are used to show the locations of substrates that are represented by too few samples to map as polygons at the map scale.

Thematic Maps—Substrate Mobility, Fine- and Coarse-Grained Sand Distribution, and Mud Content of Substrates

Thematic substrate maps show the distribution of some specific properties of each substrate to provide information on processes of erosion, transport, and deposition and on the possible ecological significance of a substrate as it applies to the preferences of benthic species.

A substrate-mobility map (based on the presence of ripples) shows where sediment movements (resuspension, winnowing, and possible transport) occur and where sediment is immobile and likely to be a site of deposition (Valentine and Gallea, 2015, map E). A sand-fraction map (based on grain-size analyses of sediment samples) shows where fine-grained sand (4 and 3 phi) deposited from suspension is dominant and where coarse-grained sand (2, 1, and 0 phi) deposited from bed transport is dominant (Valentine and Gallea, 2015, map F). A mud-content map (Valentine and Gallea, 2015, map G) shows where mud has been transported and deposited from suspension and where the sediment contains mud in seven ranges of concentration (<1; 1 to <5; 5 to <10; 10 to <20; 20 to <50; 50 to <90; and ≥90 weight percent).

Substrate Symbols and Names

There is a need to develop a terminology that can be used to name and briefly describe individual substrates for use in text and in labelling maps. In this study, each geologic substrate is identified by a unique symbol that uses letters and numbers such as A1, A2, B, and so forth. Further, a substrate is identified and briefly described by a two-part substrate name which combines the unique identification symbol (first part) with a non-unique combination of characters (second part) that describes the major physical attributes of the substrate, including mobility (sediment ripples), sediment class, nonsediment class, and layering (tables 5–9, in back of report). For example, the two-part name of unlayered substrate A1 is A1 r_cgS which means “substrate A1—rippled, coarse-grained sand,” where coarse-grained sand is the sediment class. The two-part name of the layered substrate B is B r_cgS / i_cbG which means “substrate B—rippled, coarse-grained sand; partial veneer on immobile cobble, boulder gravel” and indicates that two sediment classes (coarse-grained sand and cobble boulder gravel) and two substrates are present.

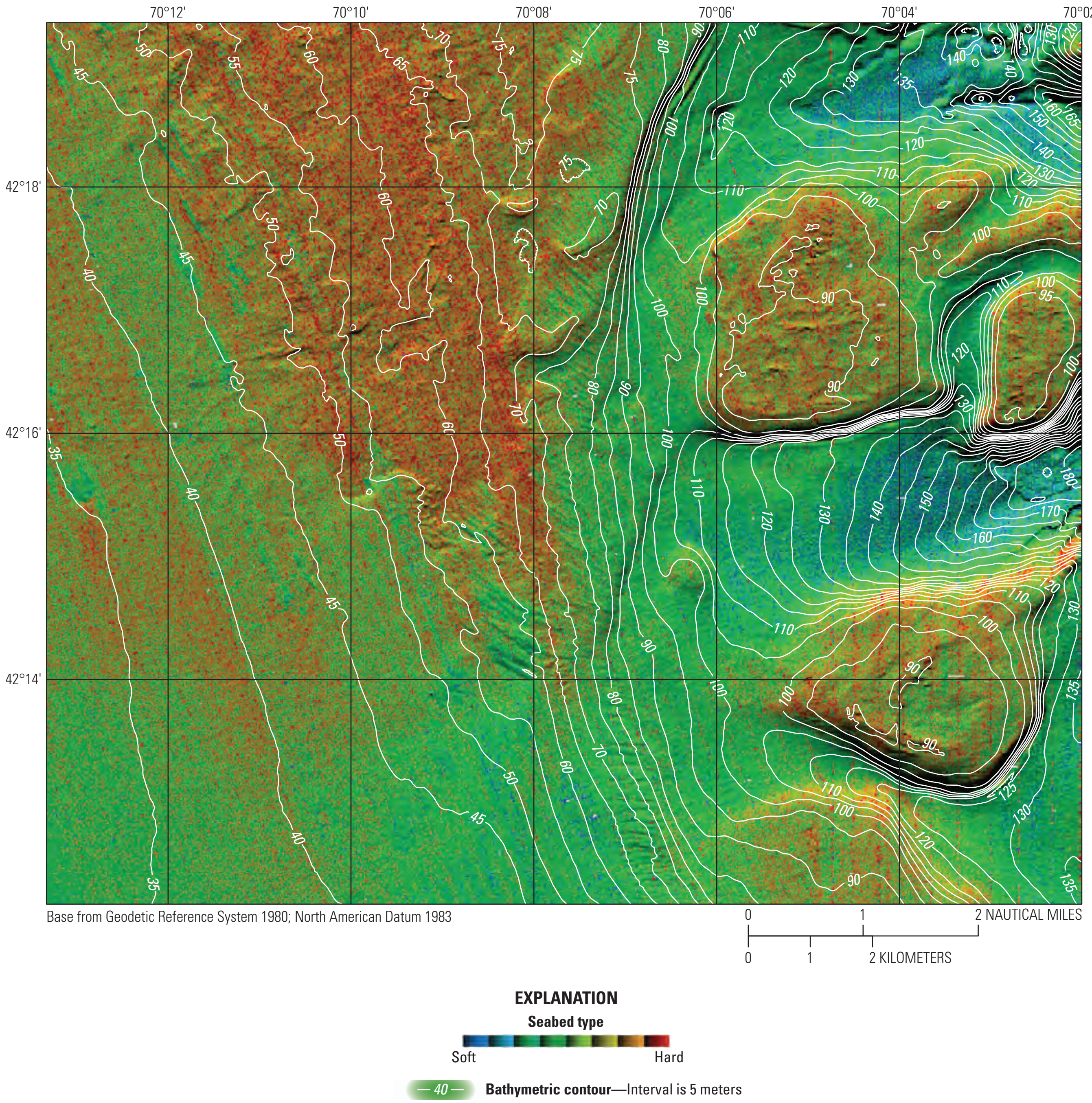
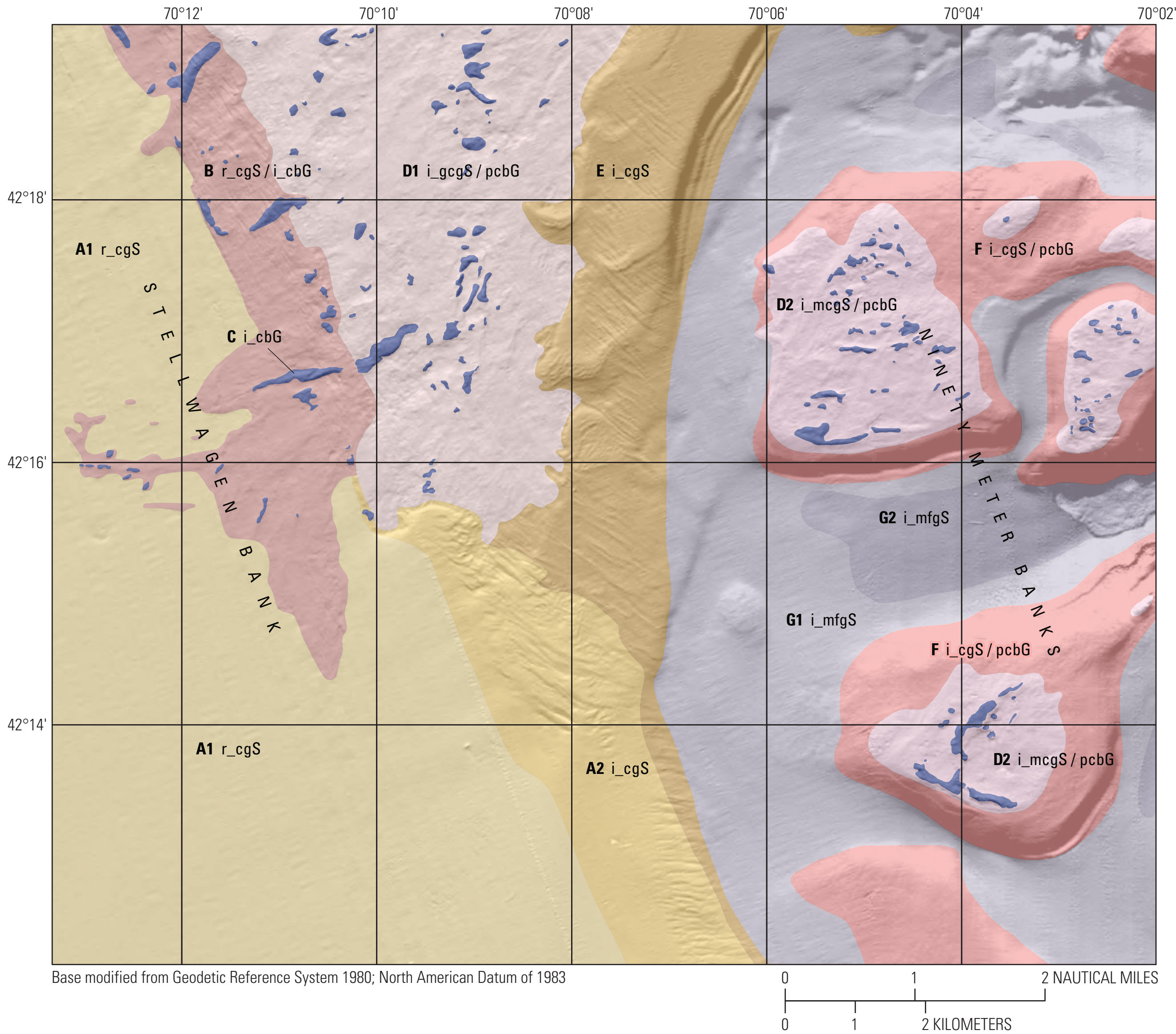


Figure 7. Distribution of the backscatter intensity of geologic substrates overlain on sun-illuminated topographic imagery in quadrangle 6 (fig. 1) of the Stellwagen Bank National Marine Sanctuary region (modified from Valentine and Gallea, 2015, map C). Backscatter intensity values are a measure of seabed hardness. Here, the hardest substrates (coarse-grained sand and gravel) are represented by orange colors, sand is represented by green colors, and the softest substrates (fine-grained sand and mud) are represented by green and blue colors. The distribution of mapped substrates is shown in figure 8.



EXPLANATION

Geologic substrate

- **A1** r_cgS — Rippled course-grained sand
- **A2** i_cgS — Immobile, course-grained sand
- **B** r_cgS / i_cbG — Rippled, course-grained sand; partial veneer on immobile cobble boulder gravel
- **C** i_cbG — Immobile, cobble, boulder gravel
- **D1** i_gcgS / pcbG — Immobile, gravelly, coarse-grained sand; partial veneer on pebble, cobble, boulder gravel
- **D2** i_mcgS / pcbG — Immobile, muddy, coarse-grained sand; partial veneer on pebble, cobble, boulder gravel
- **E** i_cgS — Immobile, coarse-grained sand
- **F** i_cgS / pcbG — Immobile, coarse-grained sand; partial veneer on pebble, cobble, boulder gravel
- **G1** i_mfgS — Immobile, muddy, fine-grained sand—Mean depth 113 meters
- **G2** i_mfgS — Immobile, muddy, fine-grained sand—Mean depth 145 meters

Figure 8. Distribution of 10 geologic substrates overlain on sun-illuminated topographic imagery in quadrangle 6 (fig. 1) of the Stellwagen Bank National Marine Sanctuary region (modified from Valentine and Gallea, 2015, map D). The seabed represents a glaciated terrain that has been modified by processes associated with three periods of sea level rise and fall since the melting of the Wisconsinan Laurentide Ice Sheet. See table 8 for explanation of abbreviations of substrate labels and for descriptions of the physical properties of the substrates.

The need to construct two-part names that are informative and brief can produce more than one substrate name in which the first part of each name (the identifying symbol) is unique but the second part of each name (the descriptive part) is not. This is the case for substrates G1 and G2 that are immobile, muddy, fine-grained sand (i_mfgS). The differences between substrates that have identical physical attributes listed in their names are documented in an accompanying table of substrate physical properties (table 8, in back of report). For example, substrates G1 and G2 have similar mean contents of fine-grained sand (78 and 77 weight percent), but they are distinguished by their mean mud and coarse-grained sand contents, with G1 having 10 weight percent each of mud and coarse-grained sand and G2 having 23 weight percent mud and 1 percent coarse-grained sand. The difference in mud content is also shown in a thematic map by Valentine and Gallea (2015, map G). It is not possible to include in the two-part substrate name all the attributes that fully describe the substrate, for the name would then be too complex for convenient use.

Habitat Mapping

Many studies have proposed methodologies for classifying and mapping habitats. Recent papers by Greene and others (2008) and Strong and others (2019) review and comment on the development of habitat classification schemes. Mapping seabed habitats is more difficult than mapping geologic substrates because the compilation of habitat maps requires both the distribution of species and the distribution of seabed properties to be known, and biologic samples are more difficult to collect and analyze than geologic samples. One approach to mapping habitats is to first map seabed geologic substrates and then identify the species and assemblages that occupy each substrate. Species often are associated with more than one substrate type.

Another approach to mapping habitats is to first map the distribution of a species, assemblage, or community, then identify the substrate properties of its area of occupation. If the area occupied by the species encompasses more than one mappable (but unmapped) substrate, the described substrate properties of the area will be the combined properties of more than one substrate. For further discussion of these two approaches to habitat mapping, see Greene and others (2007) and LaFrance and others (2014).

Recently, Cooper and others (2019) developed two different approaches to compile habitat maps of the United Kingdom's continental shelf. One is based on the analysis of 11 physical properties of the seabed and water column in which substrates are characterized by their mud, sand, and gravel content. The other is based on the identification and distribution of macrofaunal assemblages. The authors identified and mapped 12 physical and 12 biological habitats. The physical habitats occupy relatively large areas of the shelf and often include many macrofaunal assemblages. By contrast, the biological habitats occupy relatively smaller areas of the shelf, are mostly dominated by a single assemblage, and often occupy multiple physical habitats (Cooper and others, 2019, figs. 2 and 5).

Discussion

A classification to be useful is limited to as few classes as are needed to effectively organize and apply information, and the classification process requires arbitrary decisions about where to draw class boundaries. Three classification schemes for sediment grains (grades, aggregates, composite grades) and one for naturally occurring sediments (sediment classes) provide a foundation for characterizing and identifying geologic substrates. The classification of sediment grains by grain diameters into grades developed by Udden (1914) and expanded by Blair and McPherson (1999) requires the range of grain diameters in each of the grades to double as grains become coarser. This is the accepted method for organizing sedimentary grains by size, and it is the standard for comparing grain-size analyses from many sources. A grade is but one member of a continuum of grain-size classes and by itself likely does not represent a natural sediment. The grade classification of Udden (1914) was simplified by Wentworth (1922) who combined the grades into four aggregates of clay, silt, sand, and gravel. Later, Folk (1954, 1980) combined clay and silt aggregates into the mud aggregate.

During the substrate mapping process described in this study, the classification of grades based on grain diameters was modified by combining the existing 23 grades into 8 composite grades. In addition to representing specific grain-size ranges, the composite grades represent different modes of sediment transport and likely play different roles in seabed ecology. The use of composite grades makes it easier to identify substrates by reducing the complexity of the grade classification and adding interpretive meaning to it. Based on grain-size analysis, the seven clay and silt grades (5–11 phi) were combined into one composite grade of mud, which moves as suspended load and is identical to the mud aggregate of Folk (1954). The five sand grades (0–4 phi) were combined into two composite grades of fine- and coarse-grained sand that represent different modes of transport. Fine-grained sand (3 and 4 phi) moves primarily in suspension, and coarse-grained sand (0, 1, and 2 phi) is stationary or moves primarily as bedload.

Of the 11 gravel grades, only the 5 granule and pebble grades (−1 to −5 phi) could be sampled by grab sampler and evaluated by grain-size analysis. They were combined into two composite grades. $Gravel_1$ (2 to <8 millimeters [mm]) are small grains, little larger than very coarse sand (1 to <2 mm), and are unlikely to provide attachment for benthic species. $Gravel_2$ (8 to <64 mm) are larger grains more likely to provide attachment for benthic species. The content of $gravel_2$ in a substrate is a measure of the likelihood that it will serve as substrate for gravel-adapted species. Gravel that could not be sampled was evaluated using visual estimates from video and photographic imagery, and to acknowledge the qualitative nature of this data, it was separated into three composite grades—pebble gravel (including any associated granules), cobble gravel, and boulder gravel—all of which are immobile and provide attachment, feeding, and refuge surfaces for benthic species. The degree of seabed coverage of each of these gravel composite grades is left to a user to classify, if desired. Note that pebble gravel can be evaluated using grain-size analysis and analysis of video and photographic imagery.

Wentworth (1922) separated naturally occurring sediments into sediment classes based on the weight percent content of the four aggregates (clay, silt, sand, gravel) they contained as determined by grain-size analysis. He defined 10 sediment classes whose boundaries were based on arbitrarily chosen limits of weight percent content of their aggregates, each of which was treated with equal importance. Wentworth avoided an overly complex classification by limiting his class names to not more than two aggregate terms and by not using grade terms as modifiers. The 10 Wentworth sediment classes are too broadly defined to be of use in characterizing substrates.

Folk (1954, 1980) also used aggregates to define 15 naturally occurring sediment classes, which he called textural classes. His class boundaries were defined by arbitrarily chosen limits of the weight percent content of three aggregates (mud, sand, gravel). In contrast to Wentworth's decision to treat the importance of each aggregate equally, Folk chose class boundaries that emphasize the gravel content and sand-to-mud ratio in the sediments to provide information about the sedimentary processes (current speed, degree of winnowing) that formed them. Folk also added complexity to the classification by using as class modifiers the median grain diameter of the sand and gravel fractions, the dominance of clay or silt in the mud fraction, and the degree of sorting. With these modifiers, it is possible to define hundreds of potential sediment classes.

The classification of naturally occurring sediments and nonsediments proposed in this report is based on grain-size analysis of sediments that can be sampled and on visual analysis of seabed imagery for sediments and nonsediments that cannot be sampled. For sediments that can be sampled, the classification follows those developed by Wentworth (1922) and Folk (1954) with modifications and additions that create sediment classes more suitable for use in mapping substrates. They are designed to reveal the transport processes that formed them and their potential ecological role. The weight percent content of the aggregates (mud, sand, gravel) they contain is used to define a group of 13 basic sediment classes in which the mud or sand or gravel content is ≥50 weight percent and a second group of 7 basic mixed sediment classes in which mud, sand, and gravel content all are <50 weight percent. The lower limit for identifying mud and sand in a class is ≥10 weight percent, following Wentworth (1922). The lower limit for identifying gravel in a class is ≥25 weight percent, which is more than the >10 weight percent limit of Wentworth and much more than the very low 0.01 weight percent limit of Folk. Gravel grains in sediments that can be collected with a grab sampler usually lie at the small end of the grain-diameter range of 2 to <64 mm. They generally constitute a small portion of the sediment, and when present at <25 weight percent, likely provide little surface area for use by gravel-adapted species.

The 20 basic sediment classes recognized in this study can be modified by adding terms that describe the fine- and coarse-grained sand content to provide information on sediment transport processes. This approach is based on the observation that fine-grained sand moves chiefly as suspended load and coarse-grained sand moves chiefly as bedload. When these modifiers are applied to all 20 sediment classes, it is possible, for completeness, to define a total of 82 classes, although many may not occur in nature. By contrast to the sediment classifications of Folk (1954) and the related Coastal and Marine Ecological Classification Standard (Federal Geographic Data Committee, 2012), the median diameters of the sand and gravel fractions of the sediment classes described here are not used as class modifiers because the median is not considered to be a good measure of average grain size, especially if the sediment is bimodal (Folk, 1980, p. 41).

The spread of grain diameters in a sediment class (that represents either a sample or a substrate), expressed in millimeters, can be of ecological relevance. The spread of grain diameters in a mud is less than 0.1 mm and of a sand less than 2 mm, but small differences in grain diameter can have a large effect on the physical properties of a sediment and can determine the suitability of a substrate to accommodate particular groups of species. In this study, the spread of grain diameters of a sediment class is determined by calculating the cumulative range and maximum difference of grain diameters, in millimeters, for all the sand and gravel phi grades and the mud composite grade that constitute ≥10 weight percent of the sediment sample or substrate.

The classification of naturally occurring sediments based on grain-size analysis is supplemented by a classification of sediments and nonsedimentary materials based on qualitative visual analysis of seabed imagery because they cannot be sampled or are not suitable for grain-size analysis. These classes are, for example, pebble, cobble, and boulder pavements, mounds, and ridges; semiconsolidated mud outcrops; rock outcrops; and shell deposits. They can be the basal layer of a layered substrate.

Some geologic maps of the seabed show the distribution of sediments characterized by their median grain size and (or) a small number of sediment classes and provide a limited view of the nature of the seabed in its role as a substrate for living organisms. An exception is the work of Greene and others (1999, 2007, 2008) who produced a complex geology-based habitat classification based on seabed substrate types and geomorphology that used the occurrence of regional topographic features, local seabed features, seabed geology, sediment composition, sediment hardness, sediment movement, and water depth, among others, to define habitats. Their approach relies chiefly on the use of remotely sensed data and video and photographic imagery, with less emphasis on sediment grain-size analyses. Sediment composition is determined by the presence of clay, silt, mud, sand, gravel, pebbles, cobbles, and boulders. Using this classification as a guide, Greene and others (2007) introduce the concept of “potential benthic habitat” maps to identify areas of likely occupancy by species based on their known substrate preferences, not on biological sampling. To this end, Greene and others (2015) compiled a series of seabed maps of the nearshore continental shelf region in the Point Reyes National Seashore in California based on geophysical data and sediment and video sampling that mapped potential habitats of rock fish and sand lance.

In the present study, multibeam sonar imagery and video and photographic imagery of the seabed are supplemented by numerous sediment grain-size analyses to identify substrates, not habitats. Substrate descriptors include (1) the mean grain-size of each of their aggregates (sand, gravel) and composite grades (mud, fine-grained sand, coarse-grained sand, $gravel_1$, $gravel_2$) that constitute sediment classes, (2) the spread and maximum difference of grain diameters in millimeters represented by the most common phi grades, (3) nonsediment classes, (4) substrate mobility, (5) substrate layering, and (6) seabed structures. Water depth range also can be a distinguishing characteristic. A substrate classification that tried to accommodate all the variations of these properties would contain so many classes that it would be impractical to use. Therefore, substrates are identified, not classified, by their descriptors. They are named by using a unique symbol and a short sequence of terms that describe mobility, sediment and nonsediment content, and layering. The full description of substrates is provided in tabular form and in descriptive text. Seabed properties that are not considered here, but that will improve the identification and mapping of substrates in other regions, can be incorporated into the substrate characterization process outlined in this study.

The methods described here for sediment and nonsediment classification, and substrate characterization, identification, and mapping rely on a high density of sediment samples and video and photographic observations to aid in interpreting multibeam sonar backscatter and bathymetric imagery. They were developed by mapping a glaciated terrain consisting of a wide range of sedimentary environments and should be useful for mapping substrates in many different terrains.

Geologic substrate maps, combined with thematic substrate maps that show the distribution of substrate mobility, and the sand and mud content of substrates, provide a knowledge base that can be used to identify sediment transport processes, validate transport model predictions, and conduct research on the ecology of benthic species. Substrate maps provide constraints on transport models by showing the water depth limit of grain movement on the seabed, the range of grain sizes available for transport, and the locations of sediment sources and sinks. The distribution of benthic species in a mapped region can reveal their substrate and other ecological preferences and allow their potential geographic distribution to be predicted. Geologic substrate maps provide the physical framework necessary for guiding seabed research and for managing marine resources and seabed usage.

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Sediment-Classification-Related Tables and Seabed Photographs

Table 5. Guidelines for naming and abbreviating the components of sediment and nonsediment classes and the properties of substrates.

[A sediment class, as determined by grain-size analysis, contains one or more of the components listed in A below. For example, a muddy, gravelly coarse-grained sand (mgcgS) is a sediment class containing three components, mud, gravel, and coarse-grained sand, listed in order of increasing weight percent. A sediment class, as determined by visual analysis of seabed imagery, contains components listed in B below. For example, a pebble cobble gravel (pcG) is a sediment class consisting of pebbles and cobbles, not listed in order of increasing abundance. A nonsediment class listed in C below is a shell deposit, or an outcrop of rock or semiconsolidated mud. An unlayered substrate contains one sediment class (for example, muddy, fine-grained sand; mfgS) or a nonsediment class (for example, rock outcrop; R). Substrate mobility and layering properties are listed in D below. Layered substrates contain at least two sediment classes or a sediment class and a nonsediment class (for example, a rippled, coarse-grained sand partial veneer on immobile, semiconsolidated mud (r_cgS / i_scM). See figure 5 and tables 6, 7, and 9 for a summary of sediment and nonsediment classes. <, less than; >, greater than; ≤, less than or equal to; ≥, greater than or equal to]

Name and abbreviation	Portion of sediment, weight percent
A. Sediment class components based on grain-size analysis	
Mud, M	M ≥50
Muddy, m	M ≥10 to <50
Sand, S	S ≥50
Sandy, s	S ≥10 to <50
Fine-grained sand, fgS	fgS ≥50
Fine-grained sandy, fgs	S ≥10 to <50; fgS >cgS, fgS – cgS = >10
Coarse-grained sand, cgS	cgS ≥50
Coarse-grained sandy, cgs	S ≥10 to <50; cgS >fgS, cgS – fgS = >10
Coarse- and fine-grained sand, cgfgS	S ≥50; fgS >cgS, fgS – cgS = ≤10
Coarse- and fine-grained sandy, cgfgs	S ≥10 to <50; fgS >cgS, fgS – cgS = ≤10
Fine- and coarse-grained sand, fgcgS	S ≥50; cgS >fgS, cgS – fgS = ≤10
Fine- and coarse-grained sandy, fgcgs	S ≥10 to <50; cgS >fgS, cgS – fgS = ≤10
Gravel, G	G ≥50
Gravelly, g	G ≥25 to <50
B. Sediment class components based on visual analysis of seabed imagery	
Gravel, G	Presence of gravel
Pebble, p	Presence of pebbles
Cobble, c	Presence of cobbles
Boulder, b	Presence of boulders
C. Nonsediment class components based on visual analysis of seabed imagery	
Rock outcrop, R	Presence of rock outcrop
Shell deposit, Sh	Presence of shell deposit
Shelly, sh	Presence of shells
Semiconsolidated mud, scM	Presence of semiconsolidated mud outcrop
D. Properties of substrate mobility and layering based on visual analysis of seabed imagery	
Rippled, r	Presence of rippled sediment, infers mobility
Immobile, i	Presence of sediment with no ripples, infers no movement
Partial veneer on, /	Indicates layered substrates. For example, “r_cgS / i_pcbG” means “rippled, coarse-grained sand; partial veneer on immobile pebble, cobble, boulder gravel”

Table 6. Classification of naturally occurring sediments (sediment classes) based on grain-size analysis.

[Criterion: mud or sand or gravel is ≥50 weight percent of the sediment. Aggregates and composite grades are listed in order of increasing weight percent. Where sand is ≥10 weight percent and fine-grained sand and coarse-grained sand differ by ≤10 weight percent, the lesser of the two is listed first in the class name, for example, mcgfgS is muddy, coarse- and fine-grained sand, where coarse-grained sand is less than fine-grained sand (sediment class 7c). Where sand is ≥10 weight percent, and fine-grained and coarse-grained sand differ by >10 weight percent, only the greater of the two is listed in the class name, for example, mfgS is muddy, fine-grained sand, where fine-grained sand is greater than coarse-grained sand by >10 weight percent (class 7a). See figure 5 for ternary diagram showing sediment classes listed in columns 4 and 5. See table 5 for explanation of abbreviations. No., Number; <, less than; >, greater than; ≤, less than or equal to; ≥, greater than or equal to]

Sediment classified by mud, sand, and gravel content					Sediment classified by mud, fine- and coarse-grained sand, and gravel content					
Sediment composition in weight percent of mud, sand, and gravel aggregates		Sediment class			Sand composition in weight percent of fine- and coarse-grained sand composite grades			Sediment class		
		No.	Name	Abbre-viation				No.	Name	Abbre-viation
Mud, M ≥50	S<10, G<25	1	Mud	M	S <10			1	Mud	M
	S<10, G≥25	2	Gravelly mud	gM				2	Gravelly mud	gM
	S≥10, G<25	3	Sandy mud	sM	fgS > cgS	fgS – cgS =	>10	3a	Fine-grained sandy mud	fgsM
					cgS > fgS	cgS – fgS =	>10	3b	Coarse-grained sandy mud	cgsM
					fgS > cgS	fgS – cgS =	≤10	3c	Coarse- and fine-grained sandy mud	cgfgsM
					cgS > fgS	cgS – fgS =	≤10	3d	Fine- and coarse-grained sandy mud	fgcgsM
	S≥10, G≥25 S<G	4	Sandy, gravelly mud	sgM	fgS > cgS	fgS – cgS =	>10	4a	Fine-grained sandy, gravelly mud	fgsgM
					cgS > fgS	cgS – fgS =	>10	4b	Coarse-grained sandy, gravelly mud	cgsgM
					fgS > cgS	fgS – cgS =	≤10	4c	Coarse- and fine-grained sandy, gravelly mud	cgfgsgM
					cgS > fgS	cgS – fgS =	≤10	4d	Fine- and coarse-grained sandy, gravelly mud	fgcgsgM
Sand, S ≥50	M<10, G<25	5	Sand	S	fgS > cgS	fgS – cgS =	>10	5a	Fine-grained sand	fgS
					cgS > fgS	cgS – fgS =	>10	5b	Coarse-grained sand	cgS
					fgS > cgS	fgS – cgS =	≤10	5c	Coarse- and fine-grained sand	cgfgS
					cgS > fgS	cgS – fgS =	≤10	5d	Fine- and coarse-grained sand	fgcgS
	M<10, G≥25	6	Gravelly sand	gS	fgS > cgS	fgS – cgS =	>10	6a	Gravelly, fine-grained sand	gfgS
					cgS > fgS	cgS – fgS =	>10	6b	Gravelly, coarse-grained sand	gcgS
					fgS > cgS	fgS – cgS =	≤10	6c	Gravelly, coarse- and fine-grained sand	gcgfgS
					cgS > fgS	cgS – fgS =	≤10	6d	Gravelly, fine- and coarse-grained sand	gfgcgS
	M≥10, G<25	7	Muddy sand	mS	fgS > cgS	fgS – cgS =	>10	7a	Muddy, fine-grained sand	mfgS
					cgS > fgS	cgS – fgS =	>10	7b	Muddy, coarse-grained sand	mcgS
					fgS > cgS	fgS – cgS =	≤10	7c	Muddy, coarse- and fine-grained sand	mcgfgS
					cgS > fgS	cgS – fgS =	≤10	7d	Muddy, fine- and coarse-grained sand	mfgcgS
	M≥10, G≥25 M<G	8	Muddy, gravelly sand	mgS	fgS > cgS	fgS – cgS =	>10	8a	Muddy, gravelly, fine-grained sand	mgfgS
					cgS > fgS	cgS – fgS =	>10	8b	Muddy, gravelly, coarse-grained sand	mgcgS
					fgS > cgS	fgS – cgS =	≤10	8c	Muddy, gravelly, coarse- and fine-grained sand	mgcgfgS
					cgS > fgS	cgS – fgS =	≤10	8d	Muddy, gravelly, fine- and coarse-grained sand	mgfgcgS

Table 6. Classification of naturally occurring sediments (sediment classes) based on grain-size analysis.—Continued

[Criterion: mud or sand or gravel is ≥50 weight percent of the sediment. Aggregates and composite grades are listed in order of increasing weight percent. Where sand is ≥10 weight percent and fine-grained sand and coarse-grained sand differ by ≤10 weight percent, the lesser of the two is listed first in the class name, for example, mcgfgS is muddy, coarse- and fine-grained sand, where coarse-grained sand is less than fine-grained sand (sediment class 7c). Where sand is ≥10 weight percent, and fine-grained and coarse-grained sand differ by >10 weight percent, only the greater of the two is listed in the class name, for example, mfgS is muddy, fine-grained sand, where fine-grained sand is greater than coarse-grained sand by >10 weight percent (class 7a). See figure 5 for ternary diagram showing sediment classes listed in columns 4 and 5. See table 5 for explanation of abbreviations. No., Number; <, less than; >, greater than; ≤, less than or equal to; ≥, greater than or equal to]

Sediment classified by mud, sand, and gravel content					Sediment classified by mud, fine- and coarse-grained sand, and gravel content					
Sediment composition in weight percent of mud, sand, and gravel aggregates		Sediment class: No.	Sediment class: Name	Sediment class: Abbre-viation	Sand composition in weight percent of fine- and coarse-grained sand composite grades			Sediment class: No.	Sediment class: Name	Sediment class: Abbre-viation
Gravel, G ≥50	M<10, S<10	9	Gravel	G	S <10			9	Gravel	G
	M<10, S ≥10	10	Sandy gravel	sG	fgS > cgS	fgS – cgS =	>10	10a	Fine-grained sandy gravel	fgsG
					cgS > fgS	cgS – fgS =	>10	10b	Coarse-grained sandy gravel	cgsG
					fgS > cgS	fgS – cgS =	≤10	10c	Coarse- and fine-grained sandy gravel	cgfgsG
					cgS > fgS	cgS – fgS =	≤10	10d	Fine- and coarse-grained sandy gravel	fgcgsG
	M ≥10, S<10	11	Muddy gravel	mG	S <10			11	Muddy gravel	mG
	M≥10, S≥10 S<M	12	Sandy, muddy gravel	smG	fgS > cgS	fgS – cgS =	>10	12a	Fine-grained sandy, muddy gravel	fgsmG
					cgS > fgS	cgS – fgS =	>10	12b	Coarse-grained sandy, muddy gravel	cgsmG
					fgS > cgS	fgS – cgS =	≤10	12c	Coarse- and fine-grained sandy, muddy gravel	cgfgsmG
					cgS > fgS	cgS – fgS =	≤10	12d	Fine- and coarse-grained sandy, muddy gravel	fgcgsmG
	M≥10, S≥10 M<S	13	Muddy, sandy gravel	msG	fgS > cgS	fgS – cgS =	>10	13a	Muddy, fine-grained sandy gravel	mfgsG
					cgS > fgS	cgS – fgS =	>10	13b	Muddy, coarse-grained sandy gravel	mcgsG
					fgS > cgS	fgS – cgS =	≤10	13c	Muddy, coarse- and fine-grained sandy gravel	mcgfgsG
					cgS > fgS	cgS – fgS =	≤10	13d	Muddy, fine- and coarse-grained sandy gravel	mfgcgsG

Table 7. Classification of mixed, naturally occurring sediments (sediment classes) based on grain-size analysis.

[Criterion: mud, sand, and gravel each <50 weight percent of the sediment. Aggregates and composite grades are listed in order of increasing weight percent. Where sand is ≥10 weight percent and fine-grained sand and coarse-grained sand differ by ≤10 weight percent, the lesser of the two is listed first in the class name; for example, McgfgSG is mud and coarse- and fine-grained sand and gravel, where coarse-grained sand is less than fine-grained sand (sediment class 14c). Where sand is ≥10 weight percent, and fine- grained and coarse-grained sand differ by >10 weight percent, only the greater of the two is listed in the class name: for example, MfgSG is mud and fine-grained sand and gravel, where fine-grained sand is greater than coarse-grained sand by >10 weight percent (class 14a). See figure 5 for ternary diagram showing sediment classes listed in columns 4 and 5. See table 5 for explanation of abbreviations. No., Number; <, less than; >, greater than; ≤, less than or equal to; ≥, greater than or equal to]

Sediment classified by mud, sand, and gravel content					Sediment classified by mud, fine- and coarse-grained sand, and gravel content			
Sediment composition in weight percent of mud, sand, and gravel aggregates		Sediment class			Sand composition in weight percent of fine- and coarse- grained sand composite grades	Sediment class		
		No.	Name	Abbreviation		No.	Name	Abbreviation
Mud, M <50 Sand, S <50 Gravel, G <50	M ≥10, S ≥10, G ≥25	14	Mud and sand and gravel M<S<G	MSG	fgS > cgS fgS – cgS = >10	14a	Mud and fine-grained sand and gravel	MfgSG
					cgS > fgS cgS – fgS = >10	14b	Mud and coarse-grained sand and gravel	McgSG
					fgS > cgS fgS – cgS = ≤10	14c	Mud and coarse- and fine-grained sand and gravel	McgfgSG
					cgS > fgS cgS – fgS = ≤10	14d	Mud and fine- and coarse-grained sand and gravel	MfgcgSG
			Mud and gravel and sand M<G<S	MGS	fgS > cgS fgS – cgS = >10	14e	Mud and gravel and fine-grained sand	MGfgS
					cgS > fgS cgS – fgS = >10	14f	Mud and gravel and coarse-grained sand	MGcgS
					fgS > cgS fgS – cgS = ≤10	14g	Mud and gravel and coarse- and fine-grained sand	MGcgfgS
					cgS > fgS cgS – fgS = ≤10	14h	Mud and gravel and fine- and coarse-grained sand	MGfgcgS
			Sand and mud and gravel S<M<G	SMG	fgS > cgS fgS – cgS = >10	14i	Fine-grained sand and mud and gravel	fgSMG
					cgS > fgS cgS – fgS = >10	14j	Coarse-grained sand and mud and gravel	cgSMG
					fgS > cgS fgS – cgS = ≤10	14k	Coarse- and fine-grained sand and mud and gravel	cgfgSMG
					cgS > fgS cgS – fgS = ≤10	14l	Fine- and coarse-grained sand and mud and gravel	fgcgSMG
			Sand and gravel and mud S<G<M	SGM	fgS > cgS fgS – cgS = >10	14m	Fine-grained sand and gravel and mud	fgSGM
					cgS > fgS cgS – fgS = >10	14n	Coarse-grained sand and gravel and mud	cgSGM
					fgS > cgS fgS – cgS = ≤10	14o	Coarse- and fine-grained sand and gravel and mud	cgfgSGM
					cgS > fgS cgS – fgS = ≤10	14p	Fine- and coarse-grained sand and gravel and mud	fgcgSGM
			Gravel and mud and sand G<M<S	GMS	fgS > cgS fgS – cgS = >10	14q	Gravel and mud and fine-grained sand	GMfgS
					cgS > fgS cgS – fgS = >10	14r	Gravel and mud and coarse- grained sand	GMcgS
					fgS > cgS fgS – cgS = ≤10	14s	Gravel and mud and coarse- and fine-grained sand	GMcgfgS
					cgS > fgS cgS – fgS = ≤10	14t	Gravel and mud and fine- and coarse-grained sand	GMfgcgS
			Gravel and sand and mud G<S<M	GSM	fgS > cgS fgS – cgS = >10	14u	Gravel and fine-grained sand and mud	GfgSM
					cgS > fgS cgS – fgS = >10	14v	Gravel and coarse-grained sand and mud	GcgSM
					fgS > cgS fgS – cgS = ≤10	14w	Gravel and coarse- and fine-grained sand and mud	GcgfgSM
					cgS > fgS cgS – fgS = ≤10	14x	Gravel and fine- and coarse-grained sand and mud	GfgcgSM
	G<25, M≥10, S≥10	15	Sand and mud S<M	SM	fgS > cgS fgS – cgS = >10	15a	Fine-grained sand and mud	fgSM
					cgS > fgS cgS – fgS = >10	15b	Coarse-grained sand and mud	cgSM
					fgS > cgS fgS – cgS = ≤10	15c	Coarse- and fine-grained sand and mud	cgfgSM
					cgS > fgS cgS – fgS = ≤10	15d	Fine- and coarse-grained sand and mud	fgcgSM

Table 7. Classification of mixed, naturally occurring sediments (sediment classes) based on grain-size analysis.—Continued

[Criterion: mud, sand, and gravel each <50 weight percent of the sediment. Aggregates and composite grades are listed in order of increasing weight percent. Where sand is ≥10 weight percent and fine-grained sand and coarse-grained sand differ by ≤10 weight percent, the lesser of the two is listed first in the class name; for example, McgfgSG is mud and coarse- and fine-grained sand and gravel, where coarse-grained sand is less than fine-grained sand (sediment class 14c). Where sand is ≥10 weight percent, and fine- grained and coarse-grained sand differ by >10 weight percent, only the greater of the two is listed in the class name: for example, MfgSG is mud and fine-grained sand and gravel, where fine-grained sand is greater than coarse-grained sand by >10 weight percent (class 14a). See figure 5 for ternary diagram showing sediment classes listed in columns 4 and 5. See table 5 for explanation of abbreviations. No., Number; <, less than; >, greater than; ≤, less than or equal to; ≥, greater than or equal to]

Sediment classified by mud, sand, and gravel content					Sediment classified by mud, fine- and coarse-grained sand, and gravel content			
Sediment composition in weight percent of mud, sand, and gravel aggregates		Sediment class: No.	Sediment class: Name	Sediment class: Abbreviation	Sand composition in weight percent of fine- and coarse- grained sand composite grades	Sediment class: No.	Sediment class: Name	Sediment class: Abbreviation
Mud, M <50 Sand, S <50 Gravel, G <50	G<25, M≥10, S≥10	16	Mud and sand M<S	MS	fgS > cgS fgS – cgS = >10	16a	Mud and fine-grained sand	MfgS
					cgS > fgS cgS – fgS = >10	16b	Mud and coarse-grained sand	McgS
					fgS > cgS fgS – cgS = ≤10	16c	Mud and coarse- and fine-grained sand	McgfgS
					cgS > fgS cgS – fgS = ≤10	16d	Mud and fine- and coarse-grained sand	MfgcgS
	M<10, S≥10, G≥25	17	Gravel and sand G<S	GS	fgS > cgS fgS – cgS = >10	17a	Gravel and fine-grained sand	GfgS
					cgS > fgS cgS – fgS = >10	17b	Gravel and coarse-grained sand	GcgS
					fgS > cgS fgS – cgS = ≤10	17c	Gravel and coarse- and fine-grained sand	GcgfgS
					cgS > fgS cgS – fgS = ≤10	17d	Gravel and fine- and coarse-grained sand	GfgcgS
	M<10, S≥10, G≥25	18	Sand and gravel S<G	SG	fgS > cgS fgS – cgS = >10	18a	Fine-grained sand and gravel	fgSG
					cgS > fgS cgS – fgS = >10	18b	Coarse-grained sand and gravel	cgSG
					fgS > cgS fgS – cgS = ≤10	18c	Coarse- and fine-grained sand and gravel	cgfgSG
					cgS > fgS cgS – fgS = ≤10	18d	Fine- and coarse-grained sand and gravel	fgcgSG
	S<10, M≥10, G≥25	19	Gravel and mud G<M	GM	S<10	19	Gravel and mud	GM
	S<10, M≥10, G≥25	20	Mud and gravel M<G	MG		20	Mud and gravel	MG

Table 8. Properties of mapped geologic substrates in quadrangle 6 of the Stellwagen Bank National Marine Sanctuary region.

[Composite grades are listed in italics. Textural properties for unlayered substrates (A1, A2, E, G1, G2) are based on grain-size analysis. For layered substrates (B, D1, D2, F), textural properties are based on grain-size analysis of the upper substrate that partially veneers the lower substrate of combinations of pebble, cobble, and boulder gravel. The underlying gravel is identified based on video imagery. Substrate C is not listed as it consists of boulder ridges identified by seabed topography and visual inspection using video imagery. Weight percent (wt pct) values may not add to 100 owing to rounding; <1 means ≤0.5 weight percent. A sand or gravel grade or mud (>4 phi) is termed "significant" in a substrate if its mean weight percent for all samples of a substrate is ≥10. Sediment components of an unlayered substrate (or the upper substrate of a layered substrate) are listed in order of increasing weight percent in the sediment class name. Sediment components of the lower substrate indicate presence/absence, and are not listed in order of increasing areal coverage in the sediment class name. Substrate names combine a unique symbol, a mobility term, a sediment class term derived from grain-size analysis, a layering term (/) if substrate layers are present, and a sediment class term describing the lower substrate based on video and photo imagery. fgS, fine-grained sand (3 and 4 phi combined); cgS, coarse-grained sand (0, 1, and 2 phi combined); G_1, $Gravel_1$ (-1 and -2 phi combined); G_2, $Gravel_2$ (-3, -4, and -5 phi combined). No., number of samples; m, meter; min, minimum; max, maximum; mm, millimeter; <, less than; >, greater than; ≥, greater than or equal to; ~, approximately]

Geologic substrate symbol	No.	Sample water depth range; mean (m)	Significant sediment grades		Weight percent of aggregates and *composite grades* that occur in the substrate								Substrate name symbol mobility_ sediment class	Substrate name translation
			Mean weight percent, phi (φ) grades; total wt pct	Grain diameter min–max; max difference (mm)	Sam-ples	*Mud*	*fgS*	*cgS*	Sand	*G_1*	*G_2*	Gravel		
A1	128	30–56 41	2φ (14), 1φ (45), 0φ (28) 87	0.25–<2.0 ~1.75	Range Mean	*0–1* *<1*	*<1–15* *3*	*50–98* *88*	52–99 90	*<1–26* *8*	*0–21* *1*	<1–47 9	A1 r_cgS	A1—rippled, coarse-grained sand
A2	26	53–77 62	3φ (10), 2φ (19), 1φ (35), 0φ (19) 83	0.125–<2.0 ~1.875	Range Mean	*<1–1* *1*	*2–37* *11*	*32–93* *72*	44–98 83	*1–36* *11*	*0–35* *5*	1–55 16	A2 i_cgS	A2—immobile, coarse-grained sand
B	22	36–58 48	2φ (19), 1φ (40), 0φ (27) 86	0.25–<2.0 ~1.75	Range Mean	*0–1* *<1*	*2–21* *5*	*65–97* *86*	78–99 92	*<1–20* *7*	*0–8* *1*	<1–22 8	B r_cgS/i_cbG	B—rippled, coarse-grained sand; partial veneer on immobile cobble, boulder gravel
D1	28	50–83 61	3φ (14), 2φ (15), 1φ (11), -3φ (13), -4φ (13) 66	0.125–<32 ~31.875	Range Mean	*1–9* *4*	*3–46* *16*	*7–64* *34*	15–92 50	*2–31* *11*	*3–75* *34*	5–81 45	D1 i_gcgS/pcbG	D1—immobile, gravelly, coarse-grained sand; partial veneer on pebble, cobble, boulder gravel
D2	15	87–105 94	>4φ (12), 3φ (15), 2φ (21), 1φ (23), 0φ (10) 81	>0–<2.0 ~2	Range Mean	*8–22* *12*	*11–42* *22*	*34–65* *55*	55–89 76	*1–14* *8*	*0–25* *4*	3–34 12	D2 i_mcgS/pcbG	D2—immobile, muddy, coarse-grained sand; partial veneer on pebble, cobble, boulder gravel
E	31	66–122 80	3φ (16), 2φ (26), 1φ (28), 0φ (10) 80	0.125–<2.0 ~1.875	Range Mean	*2–10* *4*	*3–48* *18*	*24–87* *64*	38–98 82	*0–28* *9*	*0–26* *5*	0–53 14	E i_cgS	E—immobile, coarse-grained sand
F	21	90–148 111	3φ (17), 2φ (16), 1φ (17), 0φ (11) 61	0.125–<2.0 ~1.875	Range Mean	*5–14* *9*	*8–54* *25*	*20–65* *44*	39–91 69	*0–27* *13*	*0–32* *9*	0–54 22	F i_cgS/pcbG	F—immobile, coarse-grained sand; partial veneer on pebble, cobble, boulder gravel
G1	39	85–171 113	>4φ (10), 4φ (29), 3φ (49) 88	>0–<0.250 ~0.250	Range Mean	*2–18* *10*	*44–94* *78*	*0–39* *10*	80–97 88	*<1–5* *1*	*1–7* *1*	0–8 1	G1 i_mfgS	G1—immobile, muddy, fine-grained sand
G2	9	125–185 145	>4φ (23), 4φ (58), 3φ (19) 100	>0–<0.250 ~0.250	Range Mean	*19–29* *23*	*70–80* *77*	*0–2* *1*	71–81 77	*0–0* *1*	*0–0* *0*	0–0 1	G2 i_mfgS	G2—immobile, muddy, fine-grained sand

Table 9. Classification of naturally occurring sediments and nonsediments based on analysis of seabed imagery.

[These sediment and nonsediment classes occur as gravel pavements, mounds, and ridges; as rock and semiconsolidated mud outcrops; and as shell deposits. They can be the basal layer of a layered substrate. Nonsediment terms can be added as needed. The terms pebble, cobble, and boulder in the class name indicate presence only; they are not listed in order of increasing areal coverage]

Name	Abbreviation
Sediment class	
Gravel	G
Pebble gravel	pG
Cobble gravel	cG
Boulder gravel	bG
Pebble cobble gravel	pcG
Pebble boulder gravel	pbG
Cobble boulder gravel	cbG
Pebble, cobble, boulder gravel	pcbG
Nonsediment class	
Rock outcrop	R
Shell deposit	Sh
Semiconsolidated mud	scM

Table 10. Location, water depth, and date of seabed photographs shown in figure 6.

[Field of view dimensions are approximate. no., number; m, meter; cm, centimeter; GMT, Greenwich Mean Time; ddd, day; hh, hour; mm, minute; ss, second]

Figure 5	Station no.	Image no.	Water depth (m)	Field of view (cm)	Quad-rangle	Year	Julian date and time, GMT ddd:hh:mm:ss	Latitude, decimal degrees	Longitude, decimal degrees
5A	1999	ferl96038_q5_1999_067.jpg	30	76×51	5	1996	304:17:29:20	42.240326	−70.265068
5B	2228a	cand98022_q6_2228a_020.jpg	42	76×51	6	1998	119:20:39:04	42.276367	−70.216164
5C	3087	isbl98017_q6_3087_045.jpg	76	76×51	6	1998	198:10:21:13	42.304600	−70.120270
5D	2046	ferl96038_q5_2046_097.jpg	61	76×51	5	1996	306:16:12:40	42.236553	−70.349350
5E	978	ferl94004_q5_978_042.jpg	64	76×51	5	1994	297:13:52:50	42.209888	−70.389610
5F	2038	ferl96038_q5_2038_025.jpg	80	76×51	5	1996	306:21:07:30	42.290653	−70.351837
5G	1887	ferl96038_q5_1887_003.jpg	79	76×51	5	1996	282:08:10:30	42.291767	−70.348000
5H	2236b	cand98022_q6_2236b_076.jpg	55	76×51	6	1998	121:17:24:30	42.265465	−70.167953
5I	1695	ferl96038_q5_1695_017.jpg	34	76×51	5	1996	306:19:01:40	42.303967	−70.282944
5J	3084	isbl98017_q6_3084_028.jpg	45	76×51	6	1998	198:08:33:15	42.305683	−70.205383
5K	3412	dlwr99011_q6_3412_021.jpg	50	76×51	6	1999	079:18:48:00	42.264648	−70.167519
5L	3412	dlwr99011_q6_3412_005.jpg	50	76×51	6	1999	079:18:38:11	42.266483	−70.170685
5M	3412	dlwr99011_q6_3412_002.jpg	50	76×51	6	1999	079:18:36:05	42.266815	−70.171303
5N	3939	conn03014_q6_3939_010.jpg	45	76×51	6	2003	238:00:29:57	42.299984	−70.196663
5O	1537	dian96025_q6_1537_098.jpg	92	76×51	6	1996	143:10:06:00	42.293625	−70.081566
5P	1537	dian96025_q6_1537_099.jpg	92	76×51	6	1996	143:10:09:10	42.293201	−70.081459

Figure 6. Photographs of seabed substrates in the Stellwagen Bank region. *A*, Rippled coarse-grained sand (r_cgS), small ripples, water depth 30 meters (m); *B*, rippled, coarse-grained sand (r_cgS), large ripples, water depth 42 m; *C*, immobile, coarse-grained sand (i_cgS), water depth 76 m; *D*, immobile, muddy, coarse-grained sand (i_mcgS), water depth 61 m; *E*, immobile, muddy, fine-grained sand (i_mfgS), small burrows, water depth 64 m; *F*, immobile, fine-grained sandy mud (i_fgsM), large burrow with worm tubes, note sediment resuspension, water depth 80 m. Field of view for all images approximately 75×50 centimeters. See table 5 for substrate abbreviation definitions and table 10 for locations and dates of image collection. All photographs are by the U.S. Geological Survey.

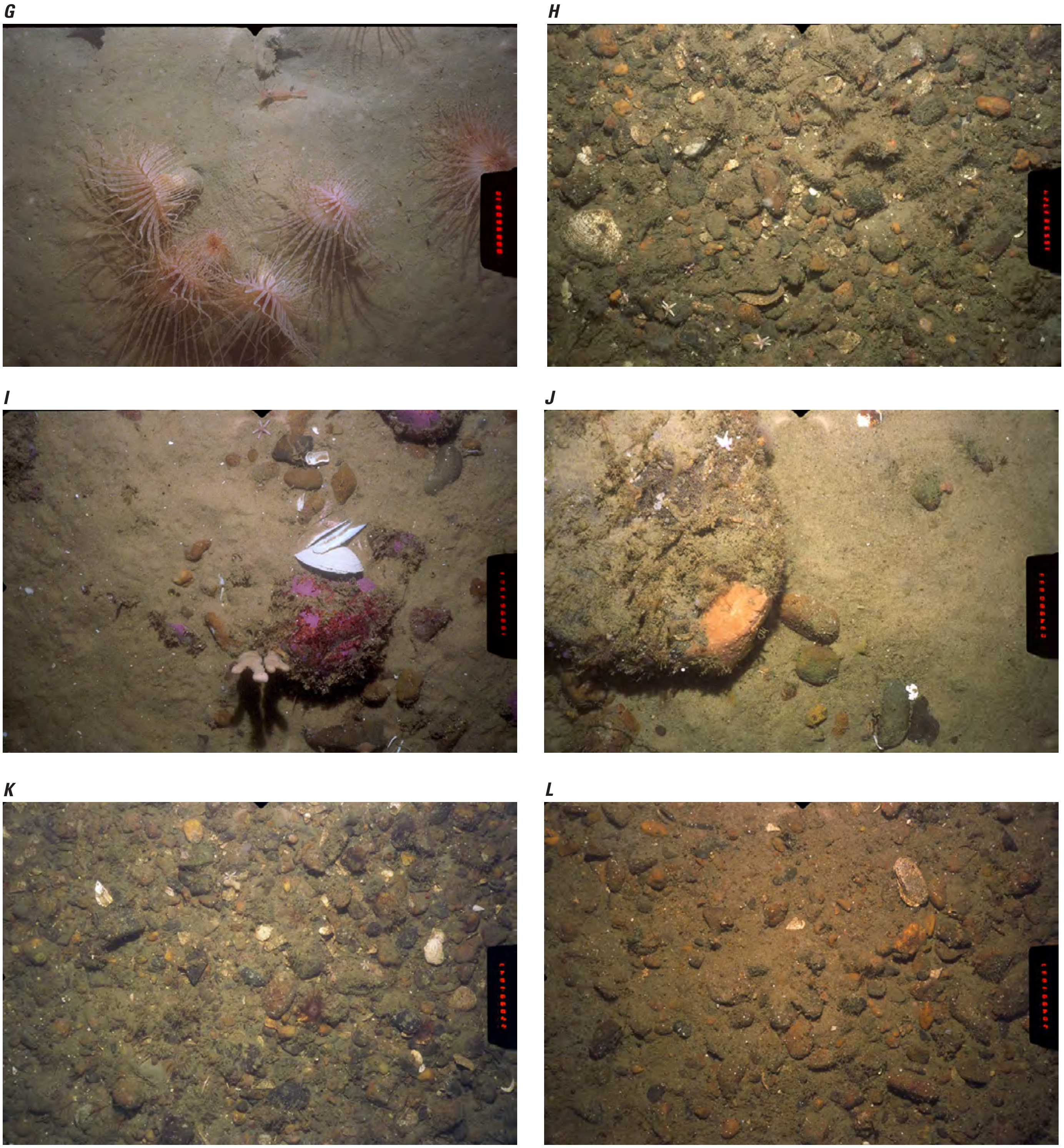

Figure 6. Photographs of seabed substrates in the Stellwagen Bank region. *G*, Immobile, fine-grained sandy mud (i_fgsM, burrow and cerianthid burrowing anemones, water depth 79 meters (m); *H*, immobile, pebble cobble gravel (i_pcG), water depth 55 m; *I*, layered substrate, rippled, coarse-grained sand partial veneer on immobile pebble, cobble, boulder gravel (r_cgS / i_pcbG), water depth 34 m; *J*, layered substrate, rippled, coarse-grained sand partial veneer on immobile pebble, cobble, boulder gravel (r_cgS / i_pcbG), water depth 45 m; *K*, layered substrate, immobile, coarse-grained sand, partial veneer on pebble gravel (i_cgS / pG), first of three images that show increasing veneer of coarse-grained sand along the same video drift (see figs. 5L, M), water depth 50 m; *L*, layered substrate, immobile, coarse-grained sand, partial veneer on pebble gravel (i_cgS / pG), second of three images that show increasing veneer of coarse-grained sand along the same video drift (see figs. 5K, M), water depth 50 m—Continued

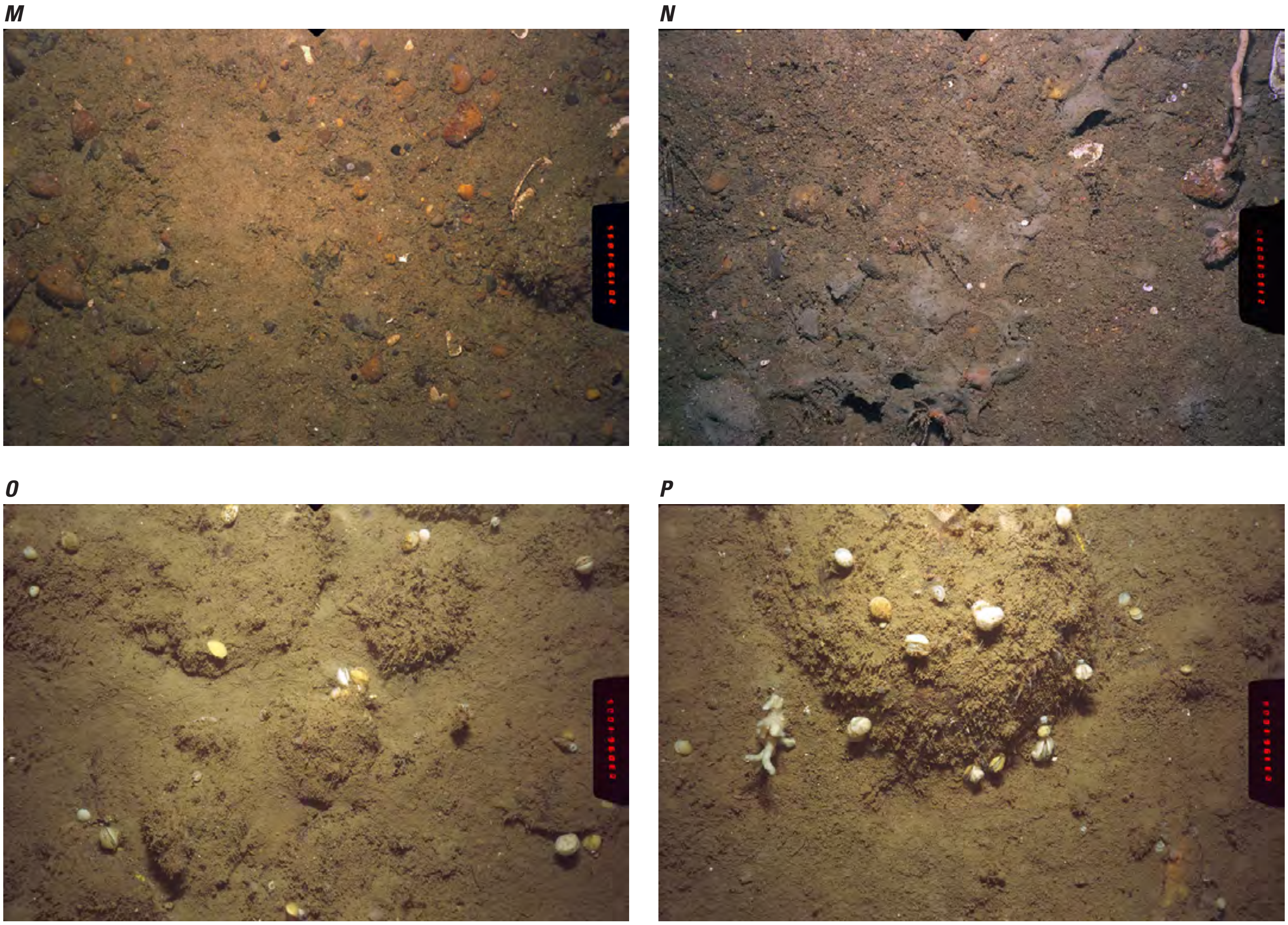

Figure 6. Photographs of seabed substrates in the Stellwagen Bank region. *M*, Layered substrate, immobile, coarse-grained sand, partial veneer on pebble gravel (i_cgS / pG), third of three images that show increasing veneer of coarse-grained sand along the same video drift (see figs. 6*K* and *L*), water depth 50 meters (m); *N*, layered substrate, immobile, coarse-grained sand, partial veneer on semiconsolidated mud (i_cgS / scM), burrows in semiconsolidated mud partially filled with coarse-grained sand, water depth 45 m; *O*, layered substrate, immobile, muddy, coarse-grained sand, partial veneer on pebble, cobble, boulder gravel (i_mcgS / pcbG), brachiopods attach to hard substrate, water depth 92 m; *P*, layered substrate, immobile, muddy, coarse-grained sand, partial veneer on pebble, cobble, boulder gravel (i_mcgS / pcbG), brachiopods attach to hard substrate, water depth 92 m.—Continued

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