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Surficial Sediments of the Eastern Bering Sea Continental Shelf: EBSSED-2 Database Documentation

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U.S. DEPARTMENT OF COMMERCE
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ABSTRACT

Sediment grain size is a fundamental property of benthic marine habitats. Its frequency distribution affects basic physical characteristics of the seafloor such as porosity, permeability, and compaction, as well as plant and animal distributions. Previous studies have reported spatial variation of sediment texture on the eastern Bering Sea (EBS) continental shelf. Many of these studies are limited to specific locations, while others characterize larger areas of the continental shelf by averaging relatively sparse data. The original studies vary in the analytical and descriptive methods used to characterize the sediment samples. The Eastern Bering Sea sediment (EBSSED) database documented here combines the original point data (n = 13,874) in a consistent manner to provide a comprehensive resource for a great variety of research on seafloor habitats of the EBS shelf. The database represents sediment variation over the study area with uncompromised (i.e., original) spatial detail. Two main types of textural data are included: 1) standardized statistics characterizing the grain size distribution of samples with % composition (e.g., gravel, sand, mud) and size-distribution parameters (e.g., mean size) and 2) sample descriptions from more subjective visual/tactile observations establishing size-grade constitutions. Two descriptive fields are added to characterize sample grain size distribution by a single, standardized variable based on the original data. These fields classify samples according to gravel-sand-mud composition using low and high-resolution schemes. The low-resolution scheme (7 classes) is designed to allow unambiguous classifications of nearly all samples (n = 13,742) including those with subjective visual/tactile descriptions. It represents the maximum number of samples according to a single common variable, providing the most spatially detailed data for the study area. The high-

resolution scheme classifies (1,458) samples with detailed granulometric data into 15 textural classes, providing greater detail regarding textural variation.

Overall, the EBSSED database is the most comprehensive and detailed source of information about surficial sediment textures in the EBS study area. Patterns observed in the data generally agree with large-scale textural maps and summaries by previous investigators, particularly a general pattern of decreasing average grain size with increasing depth and distance from shore. Those previous large-scale works used spatially smoothed data for the study area from smaller, more sparsely distributed sets of samples. The EBSSED database preserves potentially important fine-scale variation.

CONTENTS

INTRODUCTION

An important environmental attribute of coastal oceans is the unconsolidated grain size-frequency distribution that characterizes the surficial sediment texture. This data type has great utility in habitat studies seeking to explain the distribution and abundance of important biological resources. The National Marine Fisheries Service has statutory responsibility to identify and protect essential fish habitat for all life history stages of all managed species (Magnuson-Stevens Fishery Conservation and Management Act, 16 U.S.C. 1801 *et seq.*, as reauthorized by the Sustainable Fisheries Act). Progress has been somewhat limited in part because suitable data characterizing spatial variation are generally lacking and collection of new environmental data are costly.

Research has demonstrated that one of the many potential factors influencing groundfish distribution and abundance is sediment texture (McConnaughey and Smith 2000; Busby et al. 2005; Yeung and McConnaughey 2006, 2008; Ciannelli et al. 2012; McConnaughey and Syrjala 2014). Sediment properties (porosity, permeability, and resistance to displacement) are affected by the relative grain size distribution (Allen 1985, Selley 1988) and these properties directly (e.g., self-burial to reduce exposure to predators) or indirectly (e.g. suitability for essential prey organisms) affect fish habitat quality as measured by rates of growth, survival, reproduction and recruitment and overall abundance (McConnaughey and Smith 2000, Cooper et al. 2014, Hurst et al. 2015). They also have been shown to affect the performance of bottom trawls that are used to survey groundfish stocks for management purposes (Weinberg and Kotwicki 2008, Somerton et al. 2013). This report updates a previous compilation (Smith and McConnaughey 1999) with the most recent data in the EBS study area.

Surficial Sediments in the Eastern Bering Sea

Sediment Transport and Deposition

Sediment deposition dynamics on the eastern Bering Sea continental shelf have been described by Lisitsyn (1966), Sharma et al. (1972), Sharma (1974a), Knebel (1974) and McManus et al. (1977). These authors conclude that physical characteristics on the shelf both influence and reflect these processes. The extensive shelf surface constitutes a relatively shallow and level area of seafloor bounded offshore by an abrupt, steep break-in-grade at 150-170 m depth (Fig. 1). Average water depth over the shelf is 60 m, and there is a relatively uniform cross-shelf slope (i.e. shelf-width/depth-at-break) averaging < 0.0003. Prevailing sea currents produce a net northerly flow from the Pacific Ocean through Unimak Pass and out through the Bering Strait to the Arctic Ocean. This is manifested in the general northerly current direction with major deviations such as a counter-clockwise gyre in Bristol Bay (Fig. 1). Alaska mainland erosion, surface runoff, and volcanism transport sediments to the coastal environment where waves and currents disperse the material offshore. The Yukon and Kuskokwim rivers are the two largest northeast and east-central shelf river outflows in the area. Shelf surface strata generally consist of contemporary thin veneer sediments, ranging in thickness of 1.5 m to over 6 m throughout the southeastern region. Exposed relict deposits exist in the north even with considerable recent river sediments.

Observations of Surficial Sediment Texture

Previous geologic, oceanographic, and biological studies on the EBS shelf have reported textural characteristics based on surficial sediment samples (e.g., Table 1). These studies were performed during various time periods with variable geographic scope and methods due to specific project objectives and available sample-processing technology. Many studies focused on selected shelf regions and not on a comprehensive area survey (e.g., Cimberg et al. 1986; Armstrong et al. 1987).

A few comprehensive characterizations of the EBS shelf have been undertaken (Lisitsyn 1959, 1966; Sharma 1974b; Naidu 1988), based largely on combined data from previous smaller-scale studies. These reports generally describe a pattern in which grain size decreases with increasing depth and distance from shore. This is captured for the southeastern Bering Sea shelf (Bristol Bay and westward) where Sharma et al. (1972) report a classic graded shelf. This condition occurs from particle settling velocity decreasing with size (Stokes Law) along with the minimum water speed necessary to re-suspend the particles. As kinetic energy of wind-generated waves decrease with increasing depth, terrigenous grains entering coastal shallows drift with water movement until they are deposited. Deposition occurs at the depth where maximum water speed due to wind or tidal currents drop below the minimum speed required for further transport. This process effectively sorts sediment particles by size, creating a graded pattern. Johnson (1983) observed sufficient irregularities to this pattern in Bristol Bay, concluding that the dynamic equilibrium of deposition forces necessary for a fully graded condition did not occur there. She attributes the observed deviations from depth-dependent grading to variations in height and intensity of storm waves and intermittent scouring by regional alongshore currents exposing patches of relict deposits. Johnson does however acknowledge a regional trend offshore of decreased grain size with increased distance from shore despite the fine-scale irregularities.

The EBS shelf is characterized by large areas with reasonably homogenous sediments due to the relatively broad, shallow shelf and the unusually level slope of the bottom. Overall, various grades of sand predominate with significant mud concentrations occurring at greater-than-average depths. Gravel is rare and generally confined to nearshore areas because of size-limited transport.

The most comprehensive surficial texture summaries in the EBS are the maps produced by Lisitsyn (1959; 1966) and Naidu (1988; Fig. 2). These works generalize classifications over large polygonal areas, revealing large-scale patterns, features, and characteristics. They do not display all the fine-scale variation of the original (point) data used to generate the polygons due to spatial averaging.

OBJECTIVES

All available surficial sediment texture data in the EBS shelf study area are assembled in a consistent and comprehensive database. All the original (point) sample detail has been retained. Two descriptive fields applying common criteria to samples of discrete textural classes are added for standardizing disparate data. The schemes are designed to characterize variation of possible significance to fish habitat studies. We maximize the number of available samples represented by a single database variable and maintain an accurate representation of sampling density and spatial variation through the classifications. The spatial extent of the database is generally defined by the boundaries of the standard U.S. National Marine Fisheries Service (NMFS) EBS resource assessment surveys (Goddard and Walters 1998). The area conforms to the EBS shelf south of a line (~60W 50' N) that extends from a point just north of Nunivak Island to the shelf break (Fig. 3). On the east and south, the study area is bounded by the Alaska mainland, extending west to the 200 m isobath.

THE EBSSED DATABASE: COMPILATION AND CONTENT[1]

Data Sources

The database characterizes surficial sediments at 13,874 separate locations throughout the EBS study area (Fig. 3). The original data were collected during the period 1898-2014 and reported by civilian and military institutions customarily involved in marine geological, geophysical, or biological research (Table 1). In addition to original data, some of these sources contain data which were first reported in other investigations (e.g., Johnson 1983 contains data from Roberts 1976), and records were screened to prevent inclusion of these duplicates.

In addition to differences in purpose and scope, these studies also differed in the equipment used to collect samples, as well as in the methods used to describe them. The samples were collected with variations of the three basic gears commonly used for sediment sampling. Records indicate samples came from grabs (n = 4,436), corers (n = 226), or dredges (n = 7). In many cases (n = 9,294), gear type was not reported. When multiple samples were collected at a single location by means of different gear types, we include only one sample record in the database. Surface subsamples from coring devices are generally preferred because of inherently

[1]For a description of EBSSED database fields, see the Appendix.

better retention of fine fractions during retrieval. However, either gravity-cores or grabs are preferred over piston cores as they are less likely to distort the top strata.

The vertical extent of each sample varied somewhat, according to the penetrating abilities of the sampling gear used. Because of our interest in surficial properties, we restrict data from cores to the upper stratum of homogeneous sediment, as determined by the original investigator. Core data typically indicated similarity of surface sediment extending down more than 10 cm; along with the performance characteristics of the other gear types (e.g., Word 1977), indicating that our database samples generally represented the sediment to that depth or greater.

Original Sample Data

Original data in the database include sample location, water depth, and gear type, as well as institutional information (e.g., cruise, station, and sample identifiers; vessel; date) that may be useful when consulting the original reports (Table 1). Textural data result from one of two basic methods by which original investigators described sediment, with either method characterizing the complete range of grain size within the sample.

Laboratory Grain Size Analysis

In 1,064 cases, the samples were analyzed in the laboratory and various statistics characterizing the grain size distribution were computed, including the four standard measures of the mean phi, sorting coefficient (i.e., standard deviation), skewness, and kurtosis, as well as the percent of sample weight in each standard size-grade. Grain size is expressed on a logarithmic scale in units of φ (phi, the negative $\log_2$ diameter in millimeters). This has advantages for the use of standard methods in statistical analysis of grain size distributions since the latter tend toward lognormality in natural sediments (Folk 1966). Size frequency (% composition) is by weight, not number of grains. Although all statistics for a sample help describe texture, two parameters in particular each encapsulate basic characteristics of the size distribution. Mean grain size represents the size at the distribution center of gravity, while the sorting coefficient is a measure of size variation and thus an inverse indicator of size sorting (poorly sorted samples contain a relatively high degree of variation; Folk 1974). Both parameters have been shown to affect such basic sediment properties as porosity, permeability, and compaction (Allen 1985, Selley 1988). Measures of skewness and kurtosis index the symmetry and peakedness of the particle size distribution, respectively, characterizing departure from a normal (i.e., Gaussian) distribution. These last two parameters are sometimes considered when deposition sources and history are traced. Although possible significance to fish habitat quality is less apparent, they are nevertheless included for completeness.

In the original studies, the actual measures (e.g., moment; graphical) used, for the four basic distribution parameters (mean phi, sorting coefficient, skewness and kurtosis) differed somewhat from the theoretical parameters of standard statistics (see reviews by McCammon 1962, Folk 1966, Brenninkmeyer 1982). These differences are due to constraints of time and equipment in calculations involving many grains per sample. Generally, where standard geological methods of calculating the four grain size moment measures were employed, values are likely to most closely approach the standard statistical parameters (Inman 1952)[2]. Alternatively, graphical measures developed for mean φ and sorting coefficient, although varying with the formula used in

[2]Gardner (personal communication; see Table 1) and Johnson (1983) provided multiple measures (graphical and moment) of each sample parameter. The values entered in the EBSSED database for samples from these sources are moment measures.

calculation, generally approach the respective standard parameters as grain size distributions approach the Gaussian normal. As such, database values for mean size (n = 1,451) are all estimates of the same variable, as are those for the sorting-coefficient (n = 1,064)[3]. However, this is not true for skewness and kurtosis values since graphical measures of those characteristics are *not* analogs of the standard statistical parameters but rather are completely different indexes. For example, Inman's primary skewness equals his graphical mean φ estimate minus the median φ-value, divided by his graphical standard deviation ($\alpha_\varphi = (M_\varphi - Md_\varphi)/\sigma_\varphi$). This measure is likely to approximate one-sixth the value of the standard skewness (Inman 1952). Documentation and references detailing parameter calculation are in the Param. measures field in the EBSSED database, or users may wish to consult the original data sources. Users are advised when employing skewness or kurtosis in an associative study to select samples with values of the same measure (e.g., all moment measures rather than a mix of estimators). The spatial distributions of sample values of mean φ and sorting coefficient in the study area are shown in Figures 4 and 5, respectively.

[3]In a few cases (e.g., McMurray et al. 1984, U.SN-H 1955), original investigations used unconventional measures for these two parameters which were not estimates of the standard parameters mean φ and standard φ deviation. We recast these values in the appropriate statistical terms analogous to the standard parameters, for entry in the database. The original measures and the formulas used for these value changes are noted in the Param. measures field.

Grain size statistics for a sample were commonly (n = 1,451) reported in terms of composition by major size-grades, usually gravel, sand, and mud (or its subclasses silt and clay), defined on a standard scale of grain size limits (Wentworth 1922, Krumbein 1934; Table 2).[4]

Grades range from (the subclass) boulders to clay, and together include all possible particle sizes. In actual laboratory analysis, sample material was usually sorted and weighed by incremental grain size ranges of 1φ or even divisions thereof (e.g., 2-2.5φ, 2.5-3.0φ). Size classes coarser than silt were usually isolated with a series of U.S. standard sieves (e.g., ASTM standard D 422-63) and, if silt and clay fractions were of interest, they were calculated from measurements reflecting settling rates in a column of water (e.g., ASTM standard D 422-63). Alternatively, two studies each employed a different type of automated particle-size analyzer to obtain size-class fractions for all or part of the sand-size range. The analyzer used for some of the samples described by Johnson (1983) employed settling rates to calculate fractions in the -1φ to 4φ range, while the type used by GeoSea Consulting Ltd. (1999) utilized laser-light diffraction by suspended sediment to obtain fractions for all sizes finer than 0.5φ. Ultimately size-class weights were combined to determine percent composition for the major Wentworth grades and were also used to compute the distribution parameters reported[5]. Since detailed weight percentages for the individual grain size ranges were reported for only about two-thirds of the laboratory-analyzed samples, such information is not included in the database as part of the granulometric

[4]Johnson (1983) included the gravel component as part of the sand grade in reporting sample sand-silt-clay composition. Therefore, for each of the 130 samples from this source the database includes % coarse sediment (i.e., gravel or sand) but the specific % gravel or % sand are unknown.

[5]In the one case where data included comprehensive size-class composition but no distribution parameters (Sharma [1976]; 81 samples), we used the composition data to calculate mean φ and sorting coefficient (moment measures) values for the database.

descriptions. Readers wishing data of this sort are referred to the original sources (Table 1).

Field Descriptions of Texture

In the remainder of cases (n = 2,462), the original textural descriptions (sediment type in Appendix) are generally qualitative (e.g., pebbly sand, silty clay), based on more subjective visual/tactile (field) methods of evaluation. These descriptions utilize the same (root) terms as the names of size-grades in the Wentworth scale. The exceptions are a few references to stone and rock, which are interpreted as particle sizes within Wentworth's open-ended gravel range (Umbach 1976). Given the subjective nature of field methods, these are less exacting descriptions than the laboratory analyses. However, the data likely have sufficient resolution and variability to be important in fish habitat studies. Within this group, 37 samples were analyzed in the laboratory but data were reported using unconventional descriptors. In particular, 11 records (NGDC 1994a, 1994b) provide verbal descriptions of primary texture that specify composition by size grades only within certain broad percent ranges. Another 26 samples (LaFond et al. 1949, Buffington et al. 1950) report sample composition, in 10% increments only, by each of six grades comprising the grain-size scale (Emery and Gould 1948). These methods preclude reporting of grain size statistics in the standard format of this database; hence they are grouped with the other purely descriptive data.

New Textural Classifications

In addition to the original textural descriptions, the database includes two fields that each independently and unambiguously classifies samples into sets of common textural types, based on the occurrence of gravel, sand, and mud specified by the original data. These two classification schemes differ in the level of detail expressed concerning sample texture, but each takes advantage of different attributes of the original data to produce new data with likely importance for habitat studies. The schemes are both based on the standard textural classifications developed by Folk (1954, 1974) and are defined on different gravel-sand-mud ternary diagrams designed to accommodate the information content of the original geological descriptions (Figs. 6a, 6b).

High-Resolution Classification

The high-resolution scheme (High-res. code in Appendix) classifies samples with detailed granulometric data (n = 1,458) using Folk's standard ternary diagram with 15 textural types (Fig. 6a; Table 3). Folk's diagram was selected from the various alternatives (e.g., Trefethen 1950, Shepard 1954) because it most closely reflected variability of sediments found in the study area (Fig. 7). In particular, the rather narrowly defined classes located near the right side and the base of the triangle allowed the greatest discrimination of textures in areas of the diagram with high sample density and relatively minor differences in composition. Conversely, relatively large class-areas along the left side of the diagram include relatively few samples. This conversion of granulometric data into a single categorical variable reflecting aspects of both central tendency and dispersion in the particle size distribution (Plumley and Davis 1956) was done to enable categorical habitat analysis options. Figure 8 shows the spatial distribution of sample high resolution textural classes in the study area.

Low-Resolution Classification

The low-resolution scheme (Low-res. code in Appendix) was developed so that the maximum number of samples (n = 13,742) could be represented in a common categorical variable representing texture, irrespective of the method originally used to describe the sample. This included 1,451 samples with laboratory grain size analyses, those with field descriptions based on visual/tactile methods (n = 12,291), and the 33 cases with atypical granulometric data insufficient for high-resolution classification but suitable for this scheme. All were classified according to a simplified form of Folk's (1954) standard gravel-sand-mud ternary diagram (Fig. 6b). Some of Folk's textural classes were merged in order to accommodate the less detailed descriptions. The field descriptions provided qualitative information on the grain-size grades in the sample but lacked the granulometric data allowing point representation on the ternary graph. These samples were therefore classified by matching descriptive terms with Folk's sediment-type names. However, as observations made in the field often lacked details of composition such as grade prevalence, samples could only be classified using the seven possible combinations of the three major grades (i.e., gravel, sand, and mud; Table 4). For example, textures described in the field as sandy gravel, pebbly sand, and sand coarse gravel were all assigned to the gravel/sand class combining Folk's sandy gravel and gravelly sand. It is also likely that a size class composing only a very small fraction of a sample escaped detection with field methods. Therefore, we eliminated class boundaries differentiating trace (i.e., 0.1-5%) from zero-level (0-0.1%) gravel compositions, incorporating each original slightly gravelly class as part of the appropriate new non-gravel category on the basis of sand-mud composition. Thus, for example, slightly gravelly muddy sand became part of sand/mud. A similar simplifying approach has been used by the National Geophysical Data Center (1986) to determine the primary texture of samples. Overall, the low-resolution scheme effectively pools the original granulometric and field-description data, albeit at the expense of some detail for samples analyzed in the laboratory, but nevertheless maximizes the number (n = 13,742) and spatial coverage (Fig. 9) of samples that are available for habitat analysis.

Primary Assumptions

We have made two assumptions while assembling the EBSSED database for fish habitat studies. First, in keeping with the time scale of sedimentary processes, we assume that neither new deposition nor scouring have changed textural properties on the EBS shelf significantly over the sampling period represented in the database (1898-present; Table 1). Knebel (1974) estimates average deposition rates for recent surface strata on the east-central Bering shelf at 8 to 70 cm per millennium. At these rates, sediment accumulation over a 116-year period would measure 0.93 to 8.0 cm thick. This represents a fraction of the minimum 10 cm surface interval which, as previously indicated, most of the sample descriptions represent. Also, evidence from each of eight piston cores from Bristol Bay show that the upper 1.5 m were deposited under physical conditions similar to the present (Sharma et al. 1972). Together with the degree of depositional equilibrium indicated by the overall size grading with depth, these observations suggest that present surficial sediments likely do not differ substantially from those occurring when the original samples were collected.

Secondly, classifications with our low resolution scheme included samples that were originally analyzed in the lab as well as those described more qualitatively in the field. This grouping assumes that assignments of the laboratory-analyzed samples based on our gravel-sand-mud ternary diagram were consistent with grain-size limits and minimum-composition thresholds determining size-grade inclusion in field descriptions. Strictly speaking, this probably is not the case, given the continuous nature of the grain size variable and the relative imprecision and subjectivity of field description methods. However, we do not consider this to be a significant source of error. The ternary diagram that we used to describe the texture of lab samples was a culmination of efforts by Folk (1954) and others (Wentworth 1922, Krumbein 1934) to create a standard classification system that was consistent with *de facto* practical limits and definitions used in the field, thus minimizing any discrepancies between the two methods of description.

DISCUSSION

Observations From The Data

We have produced maps showing values of textural variables at sample locations to reveal patterns and characteristics in spatial variability. Maps are of mean φ, sorting coefficient, and high-and low-resolution textural classes (Figs. 4, 5, 8, and 9, respectively). Skewness and kurtosis are not included due to the heterogeneity of the indexes used in the original studies. The data based on granulometric analysis are from 1,458 sample locations constituting relatively fine-scale, even representation of the study area (e.g., high-resolution class; Fig. 8). The combined (low-resolution) data set is even more extensive (n = 13,742) and maximizes the number of locations represented (Fig. 9). The majority of the additional data points are confined to the northern portion of Bristol Bay and along the Aleutian Chain. Therefore, the database design allows selective elimination of such a locally concentrated subset for more uniform coverage.

The ternary plot of 1,458 specific sample compositions (Fig. 7) indicates that, overall, sand is the greatest constituent of the surficial sediment in the study area, with less mud and much less gravel present. Samples composed of more than one major component usually also include sand and mud or sand and gravel; seldom are both the extreme size classes found (gravel and mud) together. This produces a distribution of points concentrated along the base and right side of the triangle, revealing at least some degree of sorting is common.

Our data reveal a trend of gradually decreasing average grain size with increasing depth and distance from the mainland shore, consistent with previous studies. This is well illustrated in Figure 4, which shows the spatial distribution of sample mean grain size (n = 1,451) expressed according to seven divisions of the range of calculated values, designed to facilitate visualization of spatial variability. The pattern is especially discernible in Bristol Bay and on the adjacent outer shelf, but is less compelling farther north.

Sample sorting values expressed according to Folk's (1974) levels (Fig. 5; n = 1,064) do not show distribution patterns quite as consistently related to features such as depth or distance offshore as does mean grain size. From north to south across the mouth of Bristol Bay is a swath of very well to moderately well-sorted samples, although these are interspersed with a few poorly and very poorly sorted ones. From this area, sorting generally becomes poorer both toward the head of the bay and southwestward toward the outer shelf. Northwest of the bay, a wide band of very well sorted and well sorted samples parallels the coast offshore from Cape Newenham on across the mouth of adjacent Kuskokwim Bay to Nunivak Island. From this region, sorting grades to very poor and extremely poor across the shelf to the outer edge.

In addition to mean φ, high-and low-resolution textural classes (Figs. 8, 9) also reveal the overall fining of sediment with increased distance offshore. The latter scheme with its set of fewer classes more effectively illustrates regional trends. The area of concentrated sampling in Togiak Bay and vicinity shows extensive fine-scale variation, with considerable representation of all types *except* gravel/sand/mud and gravel/mud. Near the Pribilof Islands, textures also vary considerably, from gravel/sand to sand/mud, due possibly to local erosion and variation in depth and current. Overall, however, samples reveal some large-scale patterns. The inner shelf (0-50

m) has isolated areas of gravel and somewhat more gravel/sand near shore, changing to sand medially, with sand/mud occurring occasionally farther offshore. The middle shelf (50-100 m) is largely sand/mud extending in a broad band from southeast to northwest and generally following the bathymetry. This pattern is disrupted by indications of a belt of sand along a line extending from the Pribilof Islands to the western tip of Nunivak Island. Surficial sediments of the outer shelf (100-200 m) are, again, largely sand/mud, disrupted by localized variation around the Pribilofs. Mud is common along the northwest margin of the middle and outer shelf portions of the study area, from around St. Matthew Island westward.

Previous EBS Shelf Descriptions

Allowing for differences among sample classification methods, the data are in general agreement with the large-scale characterizations of the eastern Bering shelf by Sharma (1974b) and Naidu (1988; Fig. 2), particularly regarding the tendency of decreasing grain size with increasing distance from the mainland shore. However, those studies presented generalizations of the distribution of textural characteristics in the form of maps which spatially averaged sample data. With regard to our study area, they were also based on a smaller, more sparsely distributed set of samples. Our data for individual sample locations naturally describe considerably finer spatial detail and reveal, within average regional grading, textural variability such as that near the Pribilof Islands or as observed by Johnson (1983) in shallow nearshore areas of Bristol Bay.

Advantages Accruing from the Database

In summary, the database presents a complete, detailed representation of the distribution of surficial sediment textural characteristics in the study area. This is expressed in terms of a number of individual variables each likely relatable in some way to biological processes. Included in these data, we have specified sediment textural type according to two schemes that classify grain size distributions at different levels of resolution. One level expresses greater detail in textural variation, while the other, although losing some detail to data standardization, describes the greatest number of samples by a single textural variable. Compared with previous large-scale studies, textural data are reported for a substantially greater number of different sample locations in the study area. In addition, we have not spatially averaged or smoothed data but instead present the values at the individual sample locations. This expresses the greatest known detail in spatial variation while allowing other investigators flexibility in the design of their studies relationships with biological variables. These considerations all compellingly support use of the EBSSED database for such purpose.

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Table 1. -- Data sources used to assemble the EBSSED database of surficial sediment textures of the eastern Bering Sea shelf. Complete citations for sources are in the Citations section or footnotes.

Source	Year of sampling	Sampling gear				Total samples
		Grab	Core	Dredge	Unknown	
Armstrong et al. (1987)	1983	81				81
Bachman (1995)[1]	1970				1	1
Barnes and Thompson (1938)	1934	31				31
Boyce (1967)	1965	3	2			5
Buffington et al. (1950)	1949	6	2	7	1	16
Cimberg et al. (1986)	1982	30				30
Gardner (1994)[2]	1976-1977	26	60			86
GeoSea Consulting Ltd. (1999)	1997	114				114
Horn et al. (1967)	1965		1			1
Hoskin (1977a)	1975	31				31
Hoskin (1977b)	1975	39				39
Johnson (1983)	1980-1981	130				130
Karl et al. (1987)	1980-1982	14	54		31	99
LaFond et al. (1949)	1947	6	4			10
McConnaughey and Syrjala (2014)	2001-2002	216				216
McMurray et al. (1984)	1983	53				53
Naidu (1985)	1976				7	7
NGDC (1994a)	1960-1970	2	4			6
NGDC (1994b)	1976-1981	2	9			11
NMFS (2006)	2006	27				27

Table 1. -- Cont.

NMFS (2008a)	2008	3				3
NMFS (2008b)	2008	47				47
NMFS (2009)	2009	40				40
NMFS (2010)	2010	38				38
NMFS (2012)	2012	25				25
NMFS (2016)	2016	14				14
NOS (2013a)	1898-2005	14	8		9,178	9,200
NOS (2013b)	1968-1997	1,564	1		53	1,618
Oshite and Sharma (1974)	1960	17				17
Roberts (1976)	1961-1970	140	79			219
SI-NMNH (1994)[3]	1985-1991	1,459				1,459
SIO-GC (1995)[4]	1957	2	2			4
Sharma (1976)	1968	80				80
USN-H (1955)	1955	31				31
USN-O (1964)	1960	4				4
Yeung and Yang (2014)	2014	11				11
Yeung and McConnaughey (2008)	2002	22				22
Yeung and Yang (2014)[5]	2010	12				12
Yeung and Yang (2017)	2011	14				14
Totals		4,348	226	7	9,293	13,874

[1]Bachman, R.T. Personal comm. 3/7/95. Sediment sample grain size statistics, unpublished data set Ber 70". U.S.N. Naval Command, Control, and Ocean Surveil. Cent.; Research, Devel., Test, and Eval. Div.; San Diego, CA.

[2]Gardner, J.V. Personal comm. 11/21/94. Sediment sample grain size statistics, unpublished data, Cruises S4-76 and S6-77. U.S. Geol. Surv., Menlo Park, CA.

[3]Smithsonian Institution, Natl Museum of Nat. Hist., Washington, D.C. (SI-NMNH). 1994. Paleobiology Sediments Master File Database, *via* pers. comm. 11/29/94 with Michael Brett-Surman, Dept. of Paleobiology.

[4]Scripps Institution of Oceanography, Geological Collect. (SIO-GC). 1995. Sample descriptions from cruises MUKB on RV *Baird* and MUKH on RV *Horizon*, via pers. comm. 1/30/95 with Warren Smith, Geological Collections. San Diego, CA.

[5]FV *Alaska Knight / Vesteraalen* (3 Jun. - 6 Aug.): Cruise Synopsis for the 2014 eastern Bering Sea continental shelf bottom trawl survey of groundfish and invertebrate resources. Available Alaska Fish. Sci. Cent., 7600 Sand Point Way NE, Seattle WA 98115.

Table 2. -- Scale by Wentworth (1922) classifying sediment particles according to the diameter expressed in units of φ (phi, the negative $\log_2$ of the diameter in millimeters).

Major grade	Phi (φ) limits		Wentworth size class
	Lower	Upper	
	<-8	-8	boulder
	-8	-6	cobble
	-6	-2	pebble
gravel	-2	-1	granule
	-1	0	very coarse sand
	0	1	coarse sand
	1	2	medium sand
	2	3	fine sand
sand	3	4	very fine sand
	4	5	coarse silt
	5	6	medium silt
	6	7	fine silt
	7	8	very fine silt
mud	8	>8	clay

Table 3. -- Frequency of occurrence of high-resolution textural classes among 1,458 sediment samples in the eastern Bering Sea study area. One of 15 class names was unambiguously assigned to each sample having detailed granulometric data, according to gravel-sand-mud composition as shown on Folk's (1954) ternary diagram (Figs. 6a, 7).

High-resolution class (code)	Frequency
gravel (G)	10
sandy gravel (sG)	59
muddy sandy gravel (msG)	11
muddy gravel (mG)	1
gravelly sand (gS)	43
gravelly muddy sand (gmS)	13
gravelly mud (gM)	5
slightly gravelly sand ([g]S)	287
slightly gravelly muddy sand ([g]mS)	49
slightly gravelly sandy mud ([g]sM)	28
slightly gravelly mud ([g]M)	2
sand (S)	342
muddy sand (mS)	264
sandy mud (sM)	284
mud (M)	60

Table 4. -- Frequency of occurrence of low-resolution textural classes among 13,742 samples in the eastern Bering Sea study area. One of 7 class names was unambiguously assigned to each sample having data sufficient for low-resolution classification, irrespective of the original method of description. Classification was based on the (significant) presence of gravel, sand, or mud (see text), illustrated by a modified version of Folk's (1954) ternary diagram (Fig. 6b).

Low-resolution class (code)	Frequency
gravel (1)	1,683
gravel/sand (2)	802
gravel/sand/mud (3)	61
gravel/mud (4)	46
sand (5)	8,352
sand/mud (6)	1,098
mud (7)	1,700

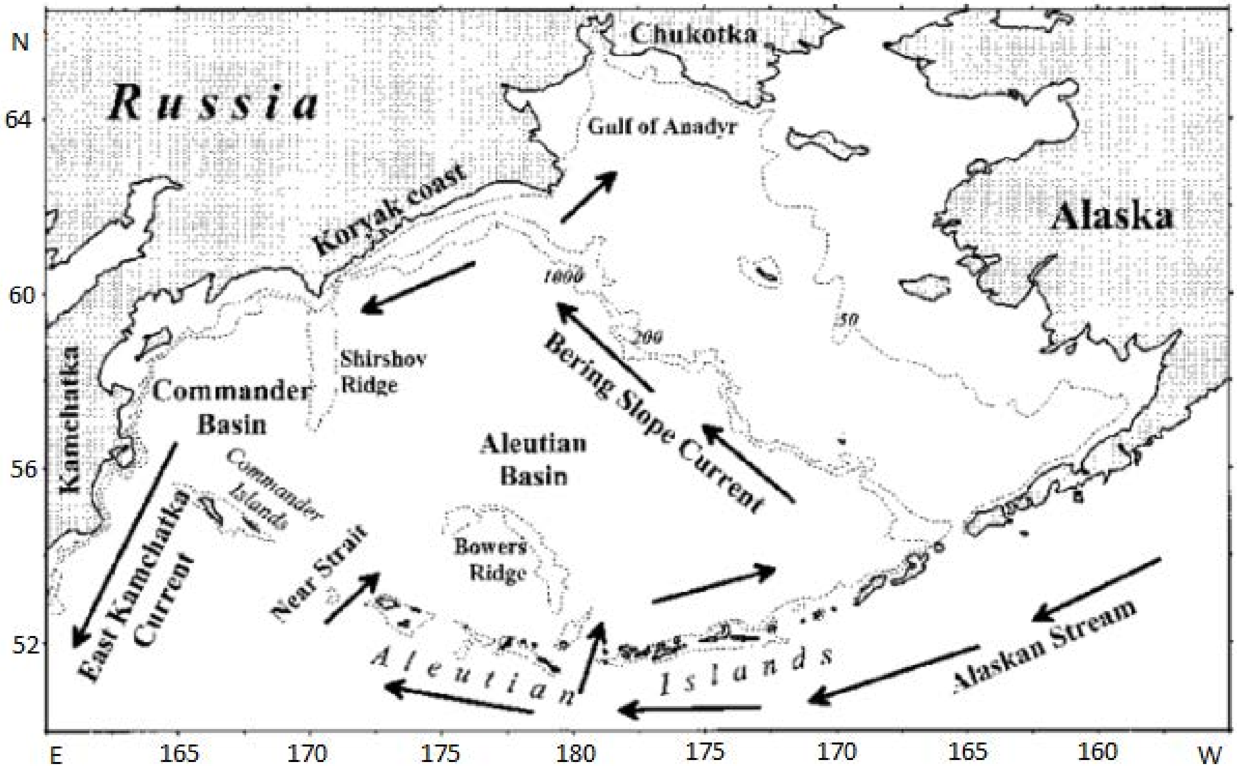

Figure 1. -- Major currents of the Bering Sea. Adapted from Stabeno (1999).

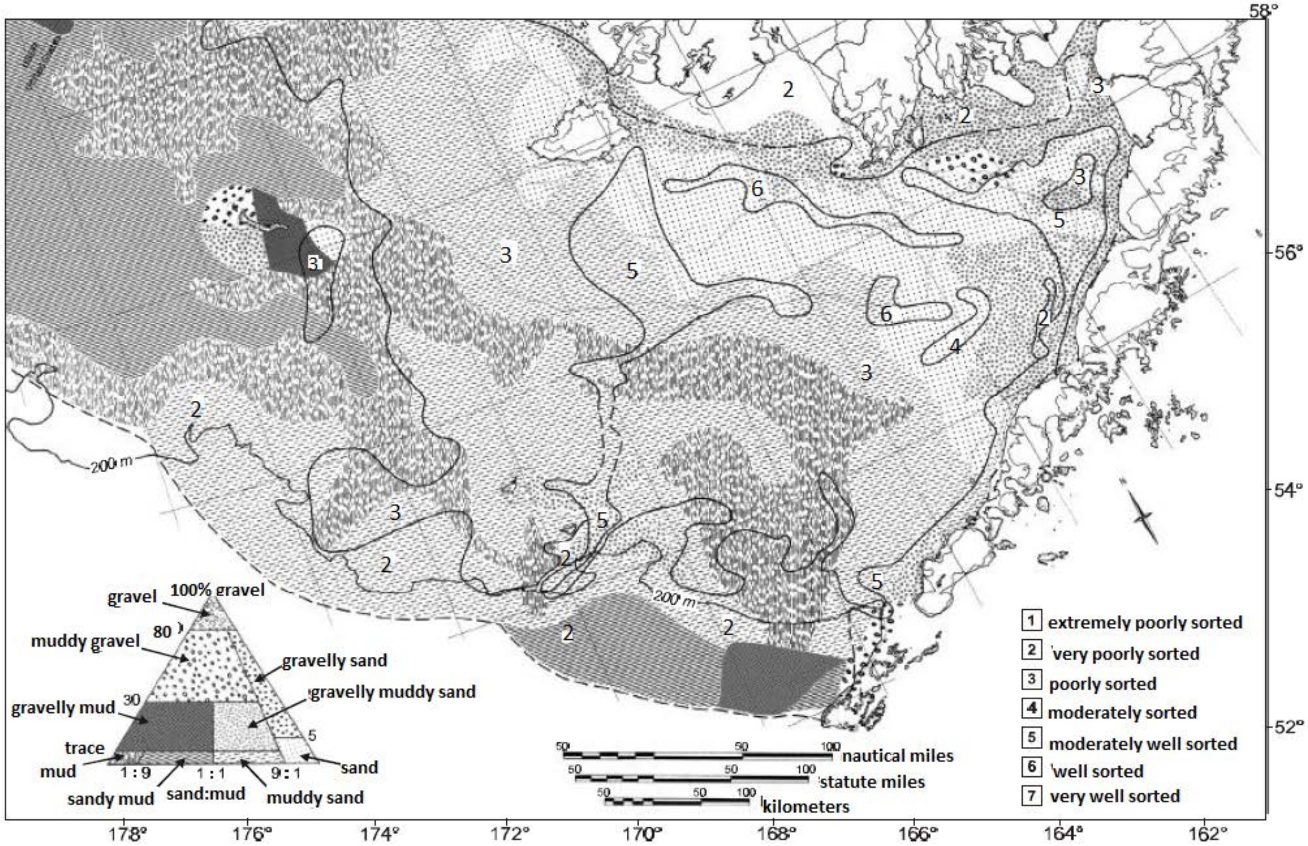

Figure 2. -- Surficial sediment textural characteristics according to Naidu (1988) for the portion of the continental shelf which is the focus of the EBSSED database. The number-code of each polygon indicates Folk's (1954) sorting level from key.

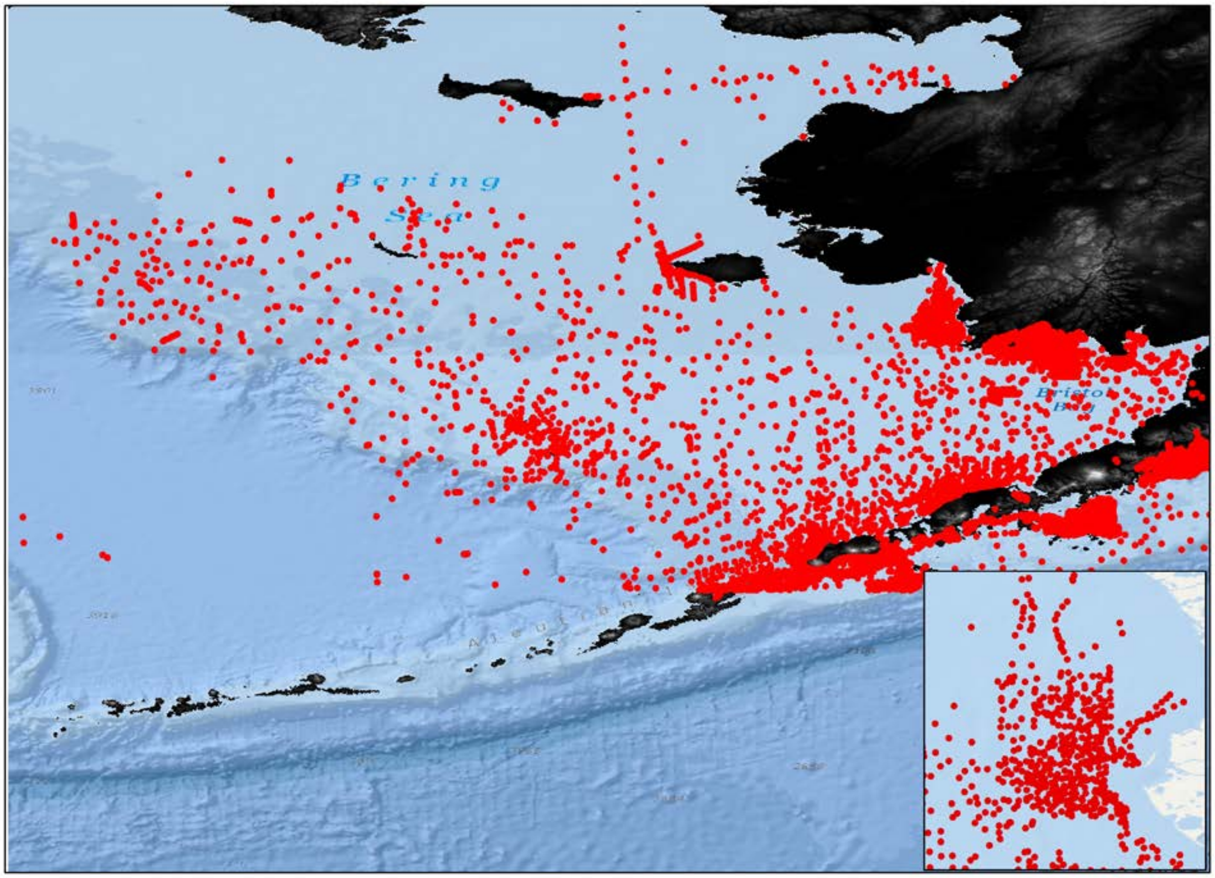

Figure 3. -- Sampling sites for EBSSED database (n = 13,874). Inset shows larger-scale view of Cape Newenham and vicinity. The sampling size increased (n = 2,587) from the original database publication with greater overall sample density, new spatial patterns, and improved localization throughout the Aleutian Chain, Bristol Bay, Cape Newenham, Nunivak Island, and the Pribilof Islands.

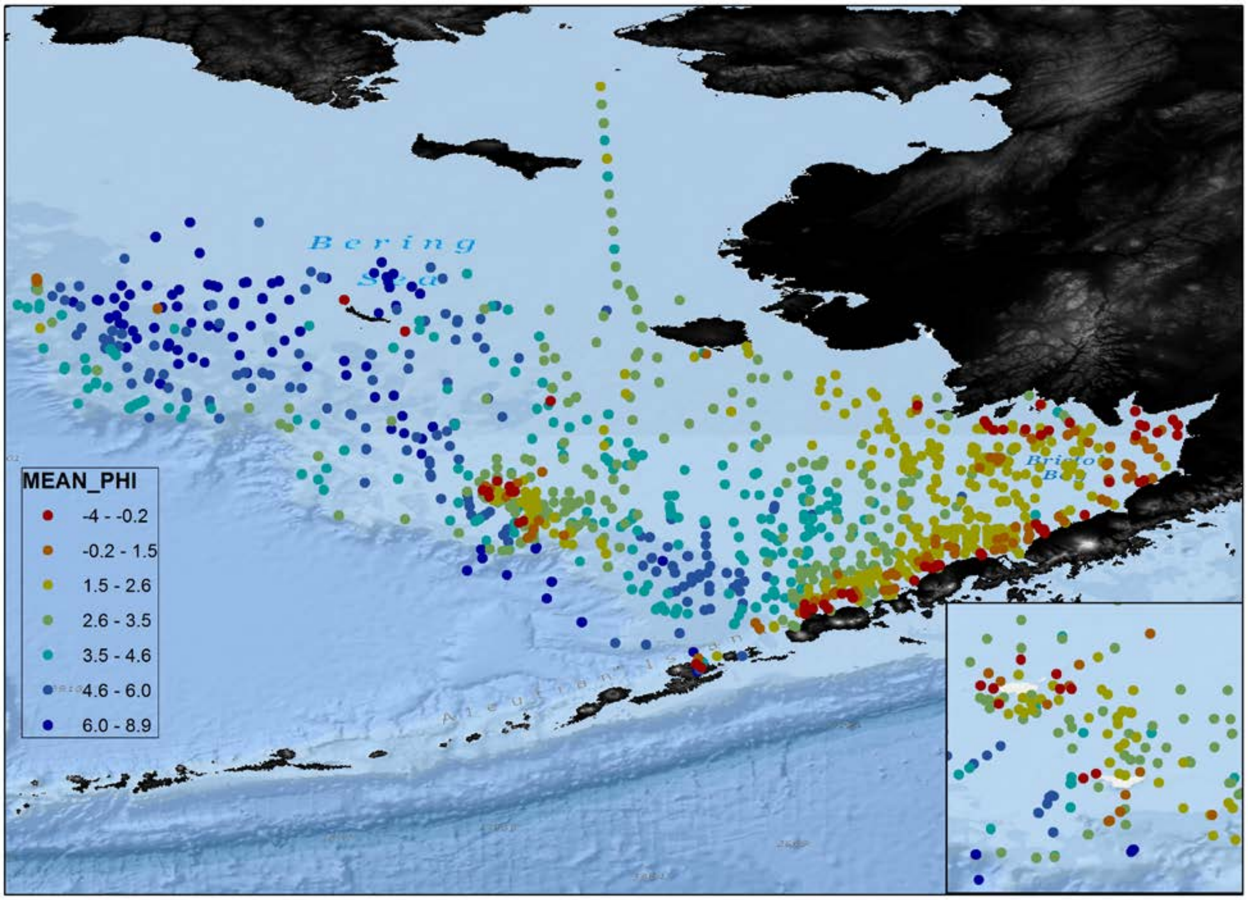

Figure 4. -- Mean phi at 1,451 sample locations, shown according to 7 divisions of the range of sample values illustrating the spatial variation. Inset is larger-scale view of St. George and St. Paul Pribilof islands and vicinity. The spatial variation of the sampling sites increased from 994 locations in the original database compilation.

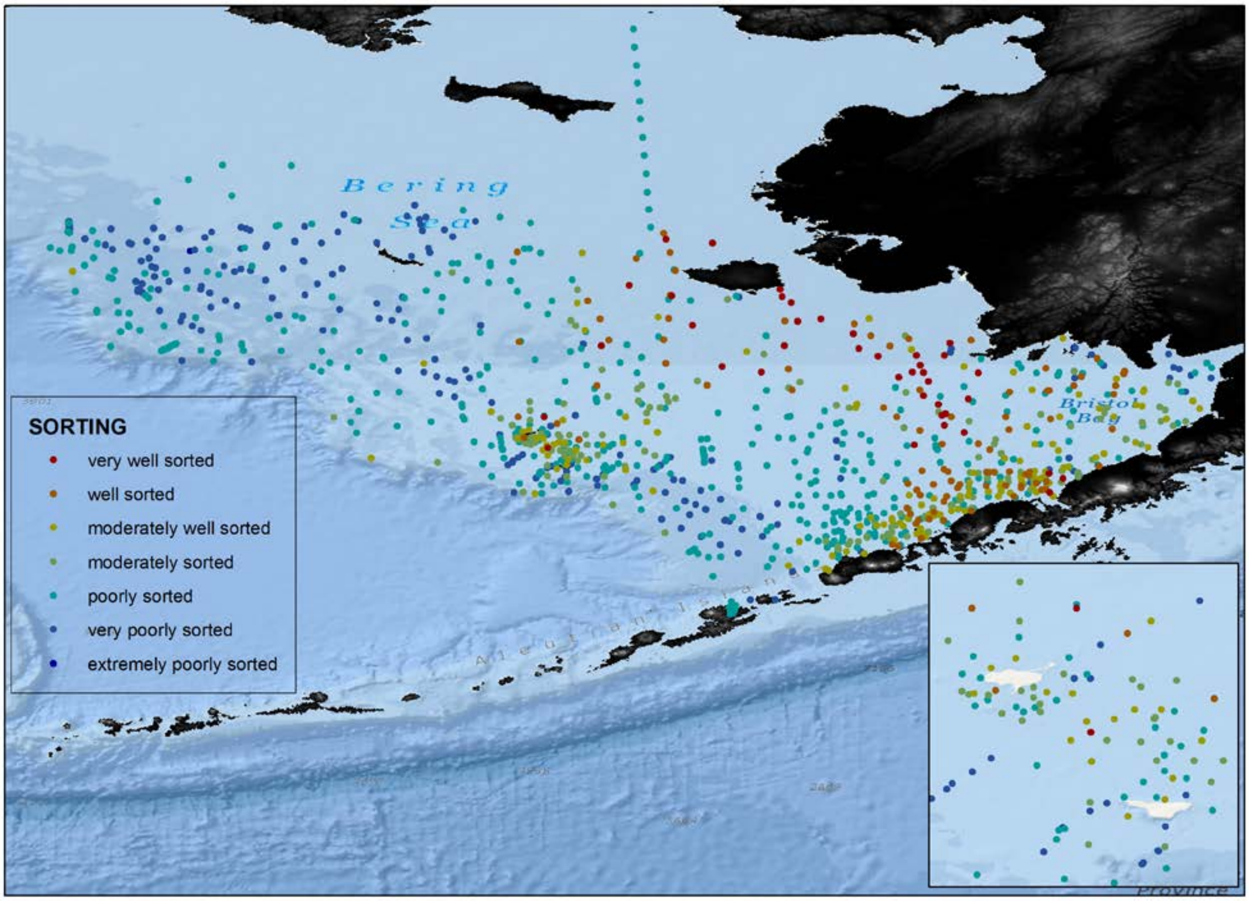

Figure 5. -- Degree of sorting at 1,064 sample locations, according to Folk's (1966) sorting levels. Insert is larger-scale view of St. George and St. Paul Pribilof islands and vicinity. Sorting sample locations increased from 1,013 sample locations in the original database compilation.

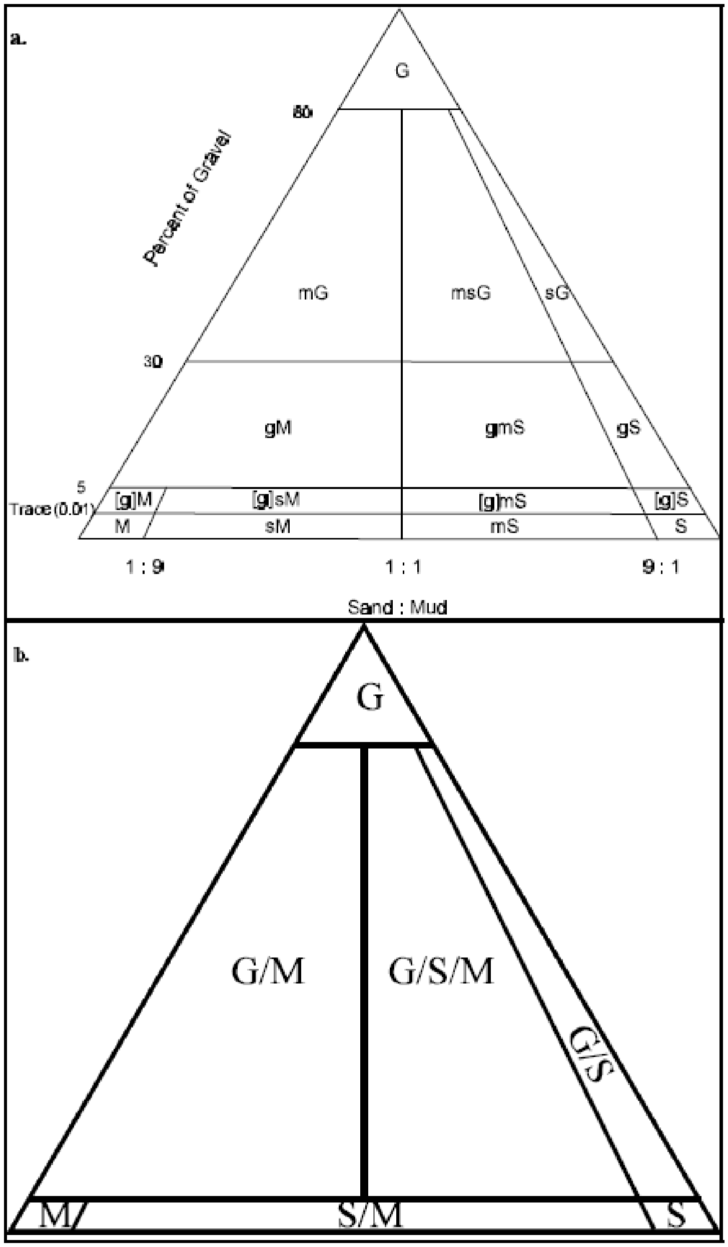

Figure 6. -- Ternary diagrams illustrating classification of sediment samples into descriptive textural classes according to gravel-sand-mud composition. Sample composition by a size grade equals 100% at the respective designated vertex of the triangle, thence decreases as the distance perpendicular from the opposite side (0%). a. High-resolution classes: Folk's (1954) 15 standard textural classes used to assign high-resolution class names to 1,458 samples originally analyzed by quantitative laboratory methods. Labels refer to class names in Table 3. b. Low-resolution classes: A simplified version of Folk's standard ternary diagram used in assigning low-resolution class names to 13,742 samples in the EBSSED database. Some internal boundaries have been removed to accommodate samples described using less detailed visual/tactile field methods, resulting in 7 distinct classes. Table 4 gives class names.

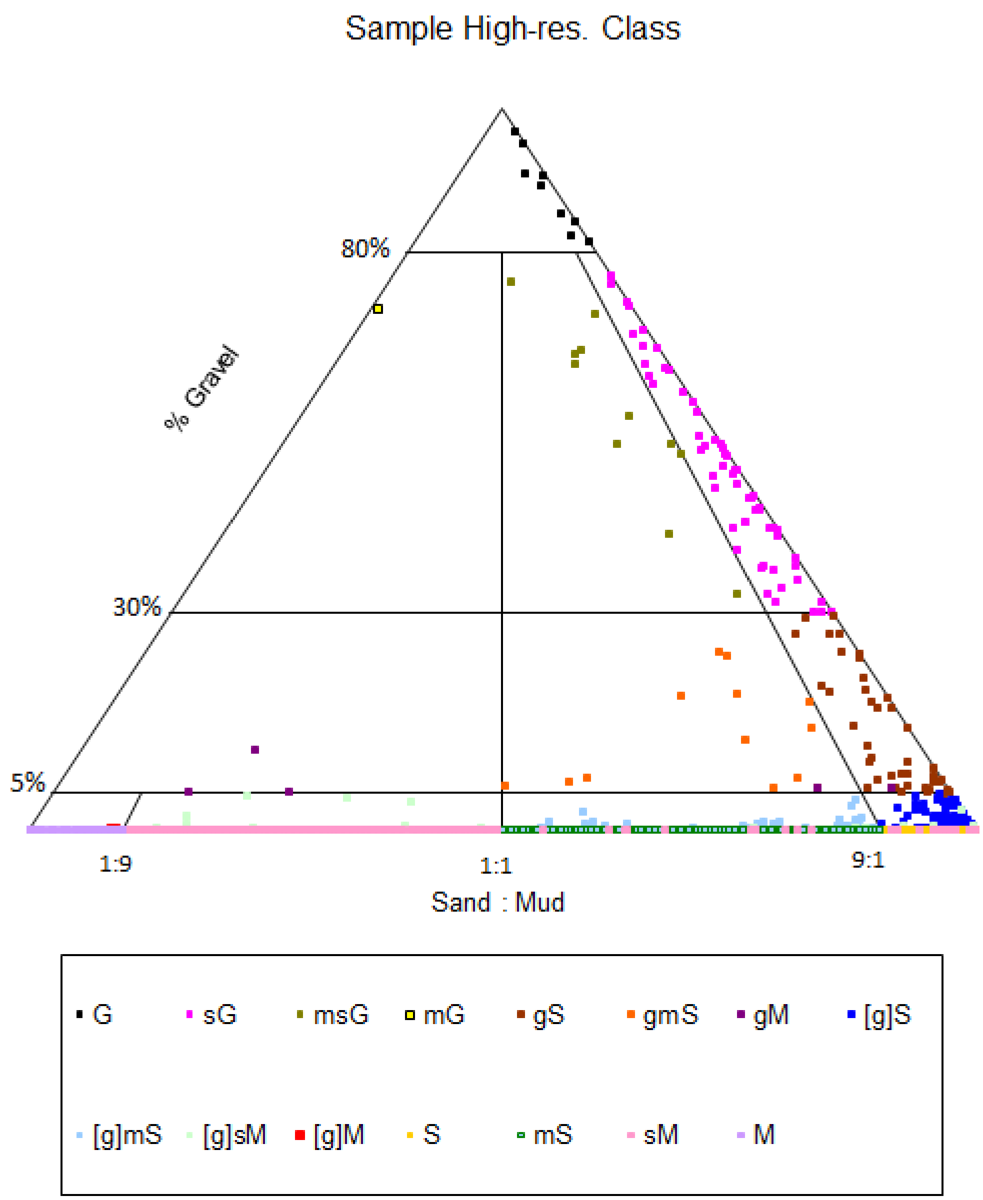

Figure 7. -- Plot of 1,458 grain size analysis samples on Folk's (1954) standard 15-class gravel-sand-mud composition diagram. Because composition (%) is represented to scale, the boundary line (at 0.01% gravel) differentiating slightly gravelly sediment types from those with essentially no gravel cannot be distinguished from the 0%-gravel base of the diagram.

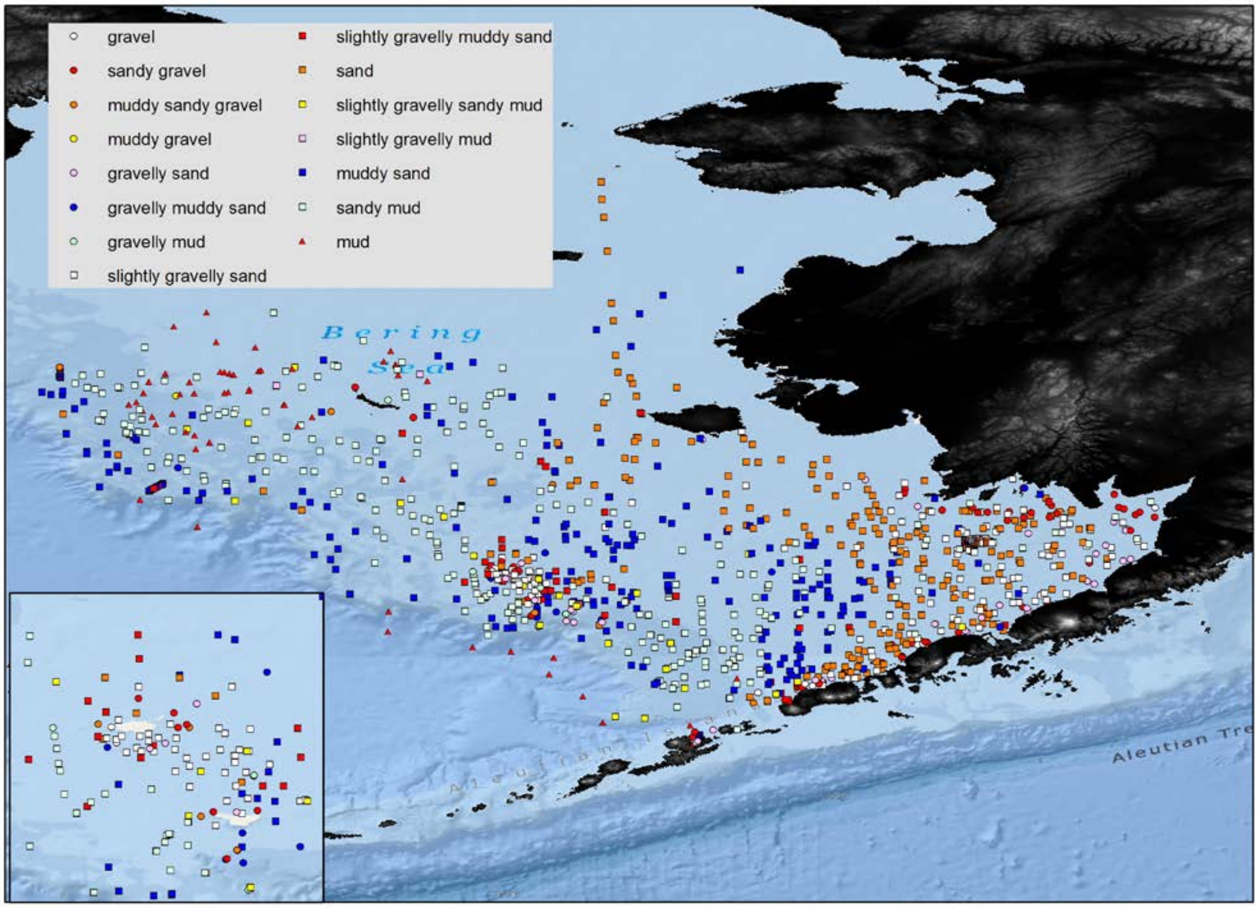

Figure 8. -- High resolution textural class of grain size analysis samples (n = 1,458). Sample size increased (n = 903) from the original database compilation.

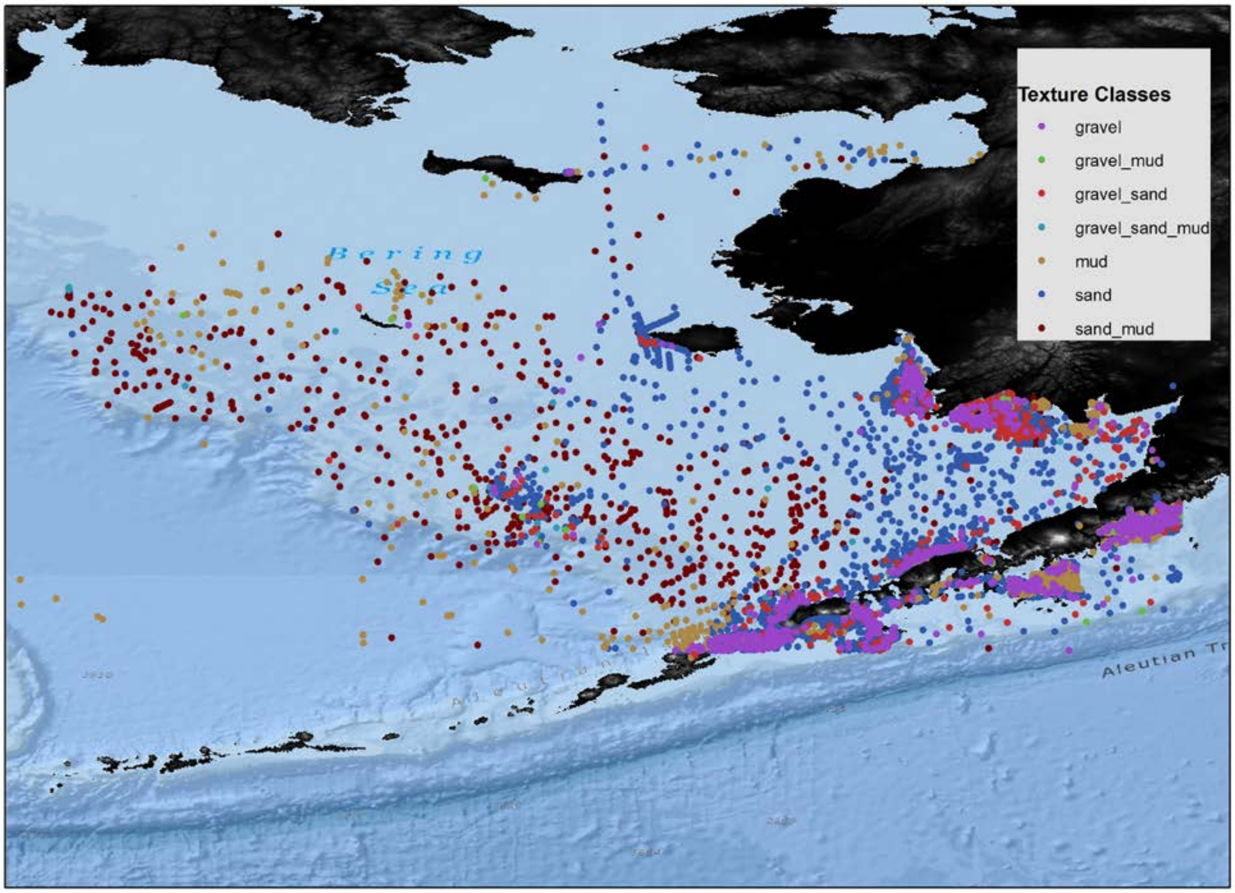

Figure 9. -- Low-resolution textural class of grain size analysis and field description samples (n = 13,742). Sample size increased (n = 2,457) from the original database compilation.

Appendix. -- Data dictionary for the EBSSED database of surficial sediments of the eastern Bering Sea.

Field name	No. of records	Comments
ID	13,874	unique record identifier (Ref. # + Cruise/Field # + Sta. # + Sample #)
Latitude	13,874	decimal degree format (dd.dd)
Longitude	13,874	decimal degree format (ddd.dd)
Depth (m)	4,657	water depth, meters
Gear	4,669	sampling gear
Depth in core (cm)	270	distance of core subsample below sediment surface (cm)
Source	13,874	original data source (see Table 1 and Citations)
Institution	13,814	sponsoring institution
Reference #	12,609	NOAA/NOS hydrographic survey # (SI-NMNH, 1994)
Cruise/Field #	2,485	cruise or operation identifier assigned by investigator
Station #	2,561	station identifier assigned by investigator
Sample #	11,972	sample identifier assigned by investigator
Ship	13,726	ship serving as sampling platform
Date	13,819	date sample collected (yymmdd; 99 for month or day indicates no data.)
Comment	2,462	pertinent information regarding sample, by original investigators or EBSSED database authors
Mean φ	1,451	mean grain diameter (φ units)
Sorting	1,064	sorting coefficient (standard deviation of grain diameter in φ units)
Skewness	874	index of symmetry of grain diameter distribution
Kurtosis	681	index of peakedness of grain diameter distribution
Param. measures	1,013	measures used as grain size parameters
% coarse	1,033	weight fraction of gravel and sand
% gravel	1,454	weight fraction
% sand	1,458	weight fraction

Appendix. -- Continued.

Field name	**No. of records**	**Comments**
% mud	1,588	weight fraction of silt and clay
% silt	859	weight fraction
% clay	859	weight fraction

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