Modeling Cape- and Ridge-Associated Marine Sand Deposits: A Focus on the U.S. Atlantic Continental Shelf

Chapter M of
Contributions to Industrial-Minerals Research

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Modeling Cape- and Ridge-Associated Marine Sand Deposits: A Focus on the U.S. Atlantic Continental Shelf

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Abstract

Cape- and ridge-associated marine sand deposits, which accumulate on storm-dominated continental shelves that are undergoing Holocene marine transgression, are particularly notable in a segment of the U.S. Atlantic Continental Shelf that extends southward from the east tip of Long Island, N.Y., and eastward from Cape May at the south end of the New Jersey shoreline. These sand deposits commonly contain sand suitable for shore protection in the form of beach nourishment. Increasing demand for marine sand raises questions about both short- and long-term potential supply and the sustainability of beach nourishment with the prospects of accelerating sea-level rise and increasing storm activity. To address these important issues, quantitative assessments of the volume of marine sand resources are needed. Currently, the U.S. Geological Survey is undertaking these assessments through its national Marine Aggregates and Resources Program (URL http://woodshole.er.usgs.gov/project-pages/aggregates/).

In this chapter, we present a hypothetical example of a quantitative assessment of cape- and ridge-associated marine sand deposits in the study area, using proven tools of mineral-resource assessment. Applying these tools requires new models that summarize essential data on the quantity and quality of these deposits. Two representative types of model are descriptive models, which consist of a narrative that allows for a consistent recognition of cape- and ridge-associated marine sand deposits, and quantitative models, which consist of empirical statistical distributions that describe significant deposit characteristics, such as volume and grain-size distribution. Variables of the marine sand deposits considered for quantitative modeling in this study include area, thickness, mean grain size, grain sorting, volume, proportion of sand-dominated facies, and spatial density, of which spatial density is particularly helpful in estimating the number of undiscovered deposits within an assessment area. A Monte Carlo simulation that combines the volume of sand-dominated-facies models with estimates of the hypothetical probable number of undiscovered deposits provides a probabilistic approach to estimating marine sand resources within parts of the U.S. Atlantic Continental Shelf and other comparable marine shelves worldwide.

Introduction

Research is underway by the U.S. Geological Survey (USGS) to find new ways of estimating potential aggregate resources in the U.S. offshore Exclusive Economic Zone (EEZ). A requirement is that these estimates reflect the degree of uncertainty in the analysis. The U.S. EEZ, as defined by Presidential declaration in 1983, is a margin extending seaward 370 km (200 nautical miles) around the United States and its territories. Of the known resources in this 12-million-km^2 area, aggregate, which includes sand, gravel, and combinations thereof, is likely to be one of the most important commodities in the near term for the United States (Williams, 1992). Marine sand and gravel is currently an important source of aggregate in Japan, the United Kingdom, the Netherlands, and other maritime countries. Currently, most nonpetroleum-resource production from the U.S. EEZ has been from marine sand deposits. The principle use of marine sand has been for beach replenishment, with ~920 million m^3 of material extracted and used since the 1920s (URL http://psds.wcu.edu/1038.asp, accessed Sept. 11, 2007). Currently, demand for additional sand to maintain and replenish beaches and other coastal landforms is increasing for both natural and manmade features and is likely to continue increasing in the near future with mitigation of erosion and sea-level rise along heavily developed coasts. A method is needed to estimate the marine sand resources available near areas undergoing coastal erosion. To reflect the uncertainty and variation in these estimates, a probabilistic approach is required.

We adopted the approach of Singer (1993), which has been used extensively for quantitative mineral-resource assessment onshore. Mineral-resource assessment is a highly formalized process, each part of which is explicitly stated. Mineral-deposit types successfully addressed by this approach have been predominately of metallic minerals (for example, porphyry copper) but also include several industrial minerals (for example, bedded barite). Numerous metallic-mineral-resource assessments have been completed in the United States, including some for the Nation as a whole (Ludington and others, 1996; Nation Mineral Resource Assessment Team, 1998) and outside, including all of Costa Rica (U.S. Geological Survey, 1987). Such assessments are now being conducted on a global scale (Schulz and Briskey, 2003). Some past activities and proposed modifications of this approach were reported by Singer (1993, 2007).

Mineral-resource models, as defined in detail below, are available for many metallic and a few industrial minerals (Cox and Singer, 1986; Bliss, 1992). Models for industrial-mineral deposits were presented by Orris and Bliss (1991, 1992). Bliss and Page (1994) constructed models for onshore sand and gravel deposits, and Bliss and others (2003) suggested some guidelines for sand and gravel assessment. To assess marine sand resources, a new set of models is needed. Several new models for cape- and ridge-associated marine sand deposits are presented here for the first time.

Acknowledgments

Development of new tools and construction of new models for assessment of marine sand deposits requires scientific insight from at least two differ types of expertise. We thank Matthew Arsenault (USGS) for providing suggestions from a marine-geologic perspective, and Keith Long (USGS) from a mineral-resource-assessment and modeling perspective. Jeffrey Waters of the U.S. Army Corps of Engineers and Gary Lore of the U.S. Minerals Management Service also provided suggestions and additions that have resulted in significant corrections and clarifications to the manuscript.

Marine-Sand-Deposit Models

Introduction

Modeling is a fundamental tool of scientific research that facilitates interpolation and extrapolation from sparse and commonly incomplete data. Many different types of model are used, but generally they are simplifications of what are perceived to be complex entities or processes. Model construction inevitably results in selecting some data and ignoring others. One unavoidable problem is that the uncertainty in model construction cannot be overcome (Gorokhovski and Nute, 1995). Modelers of most geologic systems can view them as either simple or complex; however, Ahnert (1996) suggested that nature is not necessarily either one or the other. Depending on the assumptions and approach used in the analysis of a natural system, the set of models constructed to characterize it can be more complex than necessary. Comparison of several observations leads to an abstraction in which some attributes are considered essential, while others are deliberately ignored. This approach, in turn, allows classification criteria to be identified and the natural system under investigation to be classified as one of several possible types. These types, however, are only abstractions—they are “models of reality” (Ahnert, 1996, p. 92). One particular problem that plagues all types of model is that the more assumptions, the less reliable the model (Ahnert, 1996, p. 111). A second deception can also arise with the assumption that a complex explanation is automatically better than a simple one, considering that the complex model may be more impressive (Ahnert, 1996). Complex systems, however, may not necessarily be adequately described by computer simulation using too few models. In both model construction and the design of the stochastic programs using a Monte Carlo simulation (MCS), the natural system under investigation must be adequately portrayed.

Descriptive Models

One type of model of specific interest in this study is the descriptive model (Singer and Berger, 2007), which is a systematic arrangement of all known information about a presumably unique mineral-deposit type. An important characteristic of descriptive models is that they consist of an assemblage of data that are empirical or that are found to be genetically interrelated. All shared attributes must be included in the model, even in the absence of a clear explanation as to why they are present. Descriptive models allow scientists conducting an assessment to recognize deposits that belong to a specific type. Descriptive models also provide information that can help assessment teams recognize local and regional geologic conditions associated with the deposit type. The regional-geologic guidelines in the descriptive model help in determining whether a specific geologic setting (or tract) is permissive for the occurrence of the deposit type. Specifically, the descriptive model gives guidelines allowing recognition of boundaries of areas (or tracts) where deposits occur; no deposits of the types addressed are expected to be found outside tract boundaries. This determination should be possible by using information contained in the descriptive model, even if a deposit of the type under investigation is not currently recognized as present in the assessment area. Descriptive models help sort out available data about important sites and may reveal the presence of an undiscovered deposit that is one of a specific type. These tasks are possible only if the descriptive model includes clearly recognizable and distinctive regional features. For example, the information in descriptive models is intended to allow someone who has never seen a marine sand deposit to be able to recognize one readily. The identification of marine sand deposits is complicated by the fact that many occurrences may be described as sand bearing but lack such characteristics as minimum thickness and volume to be considered a potential source of sand. An interim descriptive model for cape- and ridge-associated marine sand deposits that is suitable for deposit tract recognition and preparation is presented in appendix A.

Quantitative Models

Construction of quantitative models for marine sand deposits suitable for use in coastal construction is limited by available data. In this initial effort, we constructed quantitative models of cape- and ridge-associated marine sand deposits that were grouped together for assessment purposes. One complication is caused by the fact that although the geologic literature on marine sand is plentiful, reports that focus on marine sand deposits identified as resources suitable for use as aggregate or beach replenishment are considerably scarcer. Most reports on marine sand deposits are focused on understanding how the observed characteristics of these deposits are produced in the marine environment, both modern and historical, without regard to their economic value. One reason for this focus may be the past perception that marine sand resources are unusually large and that little additional information about resource size is need. One important factor is that considerations of end use and extraction requirements commonly make many sand deposits unsuitable because of the unacceptable contents of fine sediment, shelly debris, or coarse materials in these deposits.

Mineral-Resource Assessment

Introduction

Simply stated, the mineral-resource-assessment approach defined by Singer (1993) consists of three parts:

1. Delineation of areas, known as permissive tracts, where deposits of a given type may be expected to occur, given knowledge of the local and regional geology.

2. Estimation of the amount of minerals by using grade, tonnage, or other distributions said to be “models” of the grade, tonnage, and so on. For some industrial-mineral-deposit types, this estimate may include volume and other special characteristic distributions unique to each deposit type (for example, a distribution of mean (phi) units for marine sand deposit types).

3. Estimation of the number of undiscovered sand deposits of a specific type, with due consideration of exploration intensity and associated successes and failures within permissive tracts. Use of subjective estimates is the standard approach, for which various guidelines were outlined by Singer (2007). One guideline is the use of mineral-deposit density (MDD)—the number of deposits per unit area where they have been well explored.

All three parts are interconnected, and some may need to be repeated and refined as the assessment proceeds. This approach is greatly facilitated by a team of experts familiar with (1) the deposits being considered, (2) the areas being assessed, and (3) assessment methodologies.

Once the mineral-resource assessment has been completed, an MCS is run, as described below. The quantitative models described in part 2 are combined with estimates of the probable number of undiscovered deposits in part 3 to assess undiscovered mineral resources within the permissive tract. The product of the simulation is a probabilistic distribution. All three parts of this approach need to use mineral deposits that are consistently defined. Uncertainty and variation in deposit characteristics, such internal features as sand content, and MDD are inseparable and are incorporated into the final assessment of marine sand resources.

Before attempting to assess marine sand resources, however, several underlying factors need to be clearly understood. First, scale and dimensional properties are always important during each part of the assessment. For example, a sand body is not a cape- and ridge-associated marine sand deposit as the term is used here unless it has a sufficient volume (length, width, thickness) to justify extraction. Therefore, assessment is ultimately focused on deposits that under the most favorable circumstances are considered suitable for extraction. Such deposits normally include both geologic and economic elements in their definition.

Scale is important in defining two fundamental products of a marine-sand assessment—the permissive tract and the criteria used for recognition of marine-sand-deposit targets. Some of the same geology (as expressed by bathymetry, geophysics, side-scan sonar, and sediment-sample characteristics) can be used to help define either a permissive tract or a marine sand-deposit target, though in different ways in relation to scale. Note that bathymetry includes bottom depth, shape, slope, and geomorphology. The types of marine shelf and currently active regional processes involved (tide dominated, storm dominated, and so on) are important because they help identify the possible types of marine sand deposits present. Marine sand deposits may be currently forming, or they may be undergoing modification or destruction. Some marine sand deposits may be relict features covered by younger sediment.

The permissive tract, which is needed to meet the requirements of part 1, can encompass as area of hundreds to thousands of square kilometers that is expected to be considerably larger than that of a marine sand deposit. All undiscovered deposits are dispersed inside the tract boundaries and suggested by targets. Marine-sand-deposit targets, which are needed to meet the requirements of part 3, are those parts of the permissive tract where marine sand deposits are expected to occur. Again, the same type of geology used to define permissive tracts may be applicable here, although for marine-sand-deposit targets the focus is on those variables with values that suggest the presence of a deposit. This information is then used to construct an exploration model. The number and area of targets identified is an important guideline in making subjective estimates of the possible number of undiscovered deposits required in part 3.

Several models have been constructed that may help in identifying cape- and ridge-associated marine sand deposits but are not used directly in an MCS. This information, which includes the areas of marine sand deposits on the sea floor, can help determine whether a suspected marine-sand-deposit target has a comparable area.

Quantitative Models

Quantitative models include distribution, relation, and spatial models. Distribution models consist of frequency distributions of geologic, economic, geometric, and geotechnical variables for marine sand deposits that are members of a population identified by using a descriptive model. Compilation and analysis of the data used in model construction may also imply that these data are actually from two deposit types, not from one as initially proposed. Clarification and improved descriptive models may be one product of the data analysis. Most of the models described below are examples of distribution models, some of which can be described by using a common statistical distribution or may have an empirical distribution.

Models are needed to satisfy the requirements of part 2 of Singer's (1993) approach; without these models, an MCS cannot be run. Most deposit variables, when correctly grouped into deposit types, have either an approximately normal or log-normal distribution. Variables considered for deposit modeling include area, volume, thickness, median grain size (reported in Φ units, as discussed below), grain sorting (also reported in Φ units), and the proportion of sand-dominated facies (that is, sand content). One data source for both modeling and assessment is the USGS usSEABED database, a compilation of marine-sea-floor observations of all types covering the entire U.S. EEZ (Williams and others, 2007a). The data for the U.S. Atlantic Continental Shelf are particularly useful (Reid and others, 2005), including the interpretation by Williams and others (2007b), as well as the reports noted in the subsection below entitled "Basic Data." Additional useful references are contained in the report by Williams and others (2003). Two of the models include variables that are important for an MCS: volume and sand-dominated facies. The first model gives the distribution of material found in cape- and ridge-associated marine sand deposits, and the second model gives the proportion of material within those deposits that meets the definition of "sand," or has a Φ value of −1 to 4. Other models have been constructed that may help assessment teams characterize marine sand deposits as a group. For example, the mean-grain-size model for cape- and ridge-associated marine sand deposits may be used to compare sample data in an assessment area.

Monte Carlo Simulation

Mathematical investigations of geologic phenomena can be deterministic, probabilistic, or some combination of both. Deterministic methods progress in a fixed and predictable manner that may involve equations, and the outcome is expected to be known and certain (URL http://www.optimizationpartner.se/index.php, accessed Apr. 24, 2006). For each set of initial conditions, there is a constant outcome. Probabilistic methods, in contrast, incorporate random chance, and the outcome is not expected to be known but may be expressed as a distribution of values. For each set of initial conditions, there is a range of possible outcomes.

The MCS method, simply defined, is "a procedure that involves statistical sampling techniques in obtaining a probabilistic approximation to the solution of a mathematical or physical problem" (James and James, 1976, p. 256). The output is a probability distribution. This type of stochastic program is random but also needs to be organized with some direction (URL http://www.cs.bham.ac.uk/~wbl/thesis.glossary.html, accessed Apr. 24, 2006) when preparing an MCS program. Stochastic programs using MCS are of specific interest here. An MCS combines data about marine sand deposits as contained in models (for example, volume) with estimates of the probable number of undiscovered deposits where iterations are expected to reflect one of many states of nature (Bliss and others, 2003). The resulting distribution of sand resources is expected to represent the full range of possible outcomes within the boundaries set by the quantitative models used and estimates of the probable number of undiscovered deposits.

More scientists are using both approaches (deterministic and probabilistic) together, as evidenced by two reports that

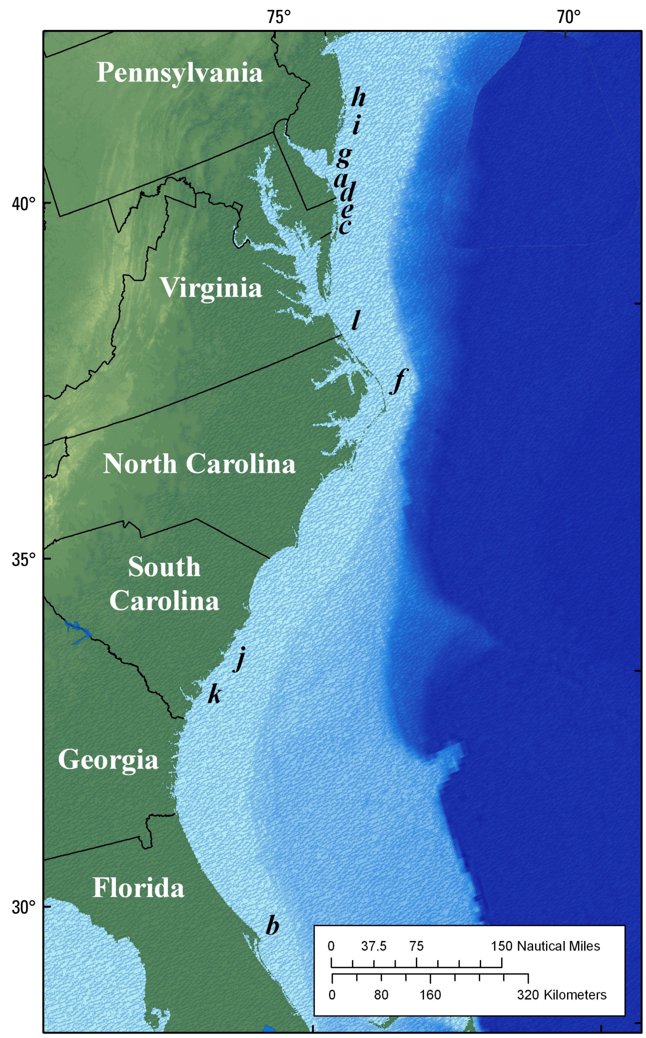

Figure 1. U.S. Atlantic Continental Shelf, showing location of study area and approximate locations of survey areas (letters) with marine sand deposits either used as data sources or mentioned in text. a, attached shoal field, Del.; b, Canaveral Shoal, Fla.; c, shoals F–M, Md.; d, Fenwick, Isle of Wright, and Weaver Shoals, Md.; e, Greater Gulf, Little Gulf Banks, and shoals B–D, Md.; f, areas 1–4, N.C.; g, shoals A–N, N.J.; h, BI–A to BI–O, N.J.; i, Avalon Shoal and Inner Sand Ridge, N.J.; j, Edisto Beach shoal and Gaskin Bank, S.C.; k, Joiner Bank shoal, S.C.; l, Sandbridge Shoal, Va. See table 1 for references associated with each survey area.

assess earthquakes (Krinitzsky, 2003) and landslides (Leynaud, and others, 2004). MCS in mineral-resource assessment has been applied to coal (Orheim, 1982), petroleum (Crovelli, 1985), and metals (Spanski, 1992).

MCS methodology has been particularly useful to some marine researchers. One of the most common applications is by scientists investigating landslides in the marine environment. Submarine slides, which are commonly triggered by earthquakes of $M>7$, can trigger tsunamis, for which Watts (2004) estimated amplitudes by using an MCS and a distribution of mass-failure size off southern California. One conclusion is that 26–33 percent of all earthquakes generate landslides with tsunamis larger than those that would have been generated by the earthquakes directly. In this study, stochastic simulation was used to supplement deterministic methods involving limited equilibrium and finite elements. An MCS was used to incorporate the uncertainties in bottom parameters for the part of the study that particularly focused on “the performance function defining the boundary between safe and unsafe (failure) domains” of the sea floor (Leynaud and others, 2004, p. 464).

Other applications of MCS methodology include its use to predict seacliff recession in the United Kingdom (Lee and others, 2001). Research by Lund and others (2003) resulted in a new approach that provides better estimates of activity coefficients in seawater by using an MCS. Activity coefficients are used in the study of seawater chemistry to calculate mineral solubilities, dissociation constants, and complex formation, among other characteristics. As illustrated and described below, a new MCS program and associated models are now available for use in resource assessments of cape- and ridge-associated marine sand deposits off the U.S. Atlantic coast (fig. 1). These modeling techniques may be applicable elsewhere in the United States and the world, as appropriate.

MCS Applications in Mineral-Resource Assessments

As described above, Singer (1993) defines a three-part approach to quantitative mineral-resource assessment. Cox and Singer (1986) prepared the first large compilation of grade-and-tonnage models needed for an MCS for both metallic and a few industrial minerals. Root and others (1992) described an MCS computer program that uses the products of quantitative mineral-resource assessments. Drew (1997) provided an insightful overview of some past progress and pitfalls in execution of this style of quantitative assessment. The MCS provides a distribution of undiscovered quantities of metals (or industrial minerals). Bliss and others (2003) also explored how aggregate assessment might proceed where the MCS is used as a sampling method of quantitative models that allows the total amount of aggregate to be calculated. The MCS needs to be iterated a sufficient number of times that the distribution of resulting values is stable. Depending on the complexity of the calculation, several thousand iterations may be sufficient, whereas Root and others (1992) recommend that 4,999 iterations are applicable to the data provided in Singer’s (1993) three-part approach.

The result of an MCS is a statistical distribution that can be used to probabilistically estimate the amount of marine sand that may be present in an assessment area. Although assessment studies predict resources yet to be extracted, several other factors come into play when the resources are actually under evaluation for development. For example, although the estimated marine sand resources may be present, they may not be extractable, owing to inaccessibility, unsuitability for dredging, preemptive use, or other economic factors, including transportation distance. These factors, however, could be addressed by constructing a second set of models that consider extraction and transportation and might be comparable to the model which provides a simplified economic filter applicable to massive sulfide deposits (Singer and others, 2000) or open-pit mining and heap-leach recovery of copper (Long and Singer, 2001).

Cape- and Ridge-Associated Marine Sand Deposits

Basic Data

Acquiring sufficient high-quality data for model construction can be a major challenge, owing to cost and general nonavailability. Data about deposits included those deposits that various State and Federal agencies have considered possible sources of marine sand and are described in the various compilations used as data sources. Nearly all deposits have volumes of >1 million m^3, whereas the smallest deposit included in the dataset has a volume of 560,000 m^3. Other deposit variables listed above have values that represent characteristics of the material within the deposits reported in these compilations. One difficulty is that some agencies have included deposits in their reports with considerable amounts of nonsand sediment.

Poor-quality data can be partly compensated for by collecting a large dataset, and this approach has been used in modeling marine sand deposits. To achieve this compensation, data from sand deposits in several different geologic settings have been compiled, but only those for cape- and ridge-associated marine sand deposits are used here. Some of these deposits are adjacent to one another but result from different geologic processes, and so we have treated them separately for modeling purposes; other deposits occur in isolation from other marine sand deposits. The data used here for modeling purposes are from published reports and other publicly available documents, including several reports prepared by State agencies with funding from the U.S. Minerals Management Service. Reports by the U.S. Army Corps of Engineers, as well as journal articles, provided additional data. Data have been compiled on >200 marine sand deposits, including those along the eastern seaboard from Massachusetts to Florida, in the U.S. Gulf of Mexico, and in southern California; other data were obtained for marine sand deposits in Nova Scotia, Puerto Rico, and Hong Kong. Some of these data may be more appropriate for sand and gravel modeling, not sand modeling, and may have been included in error, owing to an absence of grain-size information. Thus, a subset of the larger dataset has been used to construct models for cape- and ridge-associated marine sand deposits.

The data initially considered 60 sites believed to contain marine cape- and ridge-associated marine sand deposits, all on the U.S. Atlantic Continental Shelf (fig. 1; table 1), that were chosen by using the criteria of S.J. Williams (verbal commun., 2007) and the descriptive model presented in appendix A.

Several different procedures were used to test the data during model preparation. One concern was about the six deposits in South Carolina, where five deposits have volume data. These five deposits were discovered to have only small volumes, and so all data from these six sites were excluded from the models. (See subsection below entitled “Volume Model.”) In addition, comparisons were also made among data variables for survey areas grouped by State with data from four or more deposits. The single deposit reported in Delaware was included with the Maryland dataset, and the single deposits reported in Virginia and Florida were excluded. Deposits were compared by using a nonparametric Wilcoxon test or a Kruskal-Wallis test if three or more datasets were available (Conover, 1999). Nonparametric tests were also used, given both the small number of observations and the uncertainty in the type of distribution some of the variables may have. Values are replaced with ranks in these tests. Significance is reported for the test results from the JMP software (SAS Institute, Inc., 2002), a statistical package that uses a one-way chi-squared (χ^2) approximation at a specified degree of freedom (DF), the number of observations (n), and the probability p of obtaining by chance a χ^2 value larger than the one calculated. Differences among variable ranks grouped by State are significant at the 1-percent-confidence level. Significant differences among variables grouped by State are readily recognized in the standardized scores calculated by the JMP program (SAS Institute Inc., 2002, p. 112.)

Several deposits of this type probably occur elsewhere. Cape- and ridge-associated marine sand deposits are considered to be among the best sources of good-quality sand useful in beach nourishment. Several of the variables reported for those deposits include area, volume, thickness, median grain size (reported in Φ units), grain sorting (also reported in Φ units), and the proportion of sand-dominated facies. Not all variables are reported for all 54 deposits.

The correlations between variables for the full dataset reported here are considered significant at the 1-percent-confidence level. Interpretation of the reported correlations is uncertain, given the small number of observations in the dataset. However, correlations between variables need to be recognized and require MCS programs to be modified if correlated variables are used together. One variable, deposit thickness, was tested differently, owing to rejection of normal and log-normal distributions—a common observation in thickness data for other deposit types. Thickness data were compared with other variables in this study by using nonparametric procedures; that is, the values were ordered and replaced with ranks before analysis. Note that the proportion of sand-dominated facies, if not reported, is assigned as 100 percent. Many deposits lack data on the proportion of sand-dominated facies.

Modeling Sand-Deposit Variables

Introduction

We used seven variables describing cape- and ridge-associated marine sand deposits to construct models, five of which proved useful to assess quantitatively marine sand deposits. The models can be used as a reference to compare observations in permissive tracts that may suggest the presence of one or more undiscovered deposits. Five models suitable for this application are those using the following variables: (1) area, (2) thickness, (3) mean grain size, (4) grain sorting, and (5) spatial density. As described below, the area and spatial-density models can be particularly useful. Two models used by the MCS program are (1) volume and (2) sand-dominated facies. A detailed discussion follows about these and other variables useful in assessing cape- and ridge-associated marine sand deposits.

Area Model

Area data are available for 47 of the 54 cape- and ridge-associated sand deposits in the study area (fig. 1). The areas of individual deposits range from 0.24 to 239 km^2. The areas of deposits along the coasts of Maryland (n=14), North Carolina (n=4), and New Jersey (n=29) are not significantly different (χ^2=2.63, DF=2, $p>\chi^2$=0.27). The dataset can be limited by several factors, including arbitrary truncation due to water depth, jurisdictional boundaries, and other externally imposed conditions. The area data (fig. 2) are right skewed so that the x-axis layout is transformed and the data pattern is shown as if it had a log-normal distribution. (See app. B on figure format and the use of statistical distributions.) Areas are displayed in figure 2 both as a histogram and as a normal quantile-quantile (or Q–Q) plot. To test the assumption of log normality suggested in the upper part of figure 2, a Shapiro-Wilk W test (Conover, 1999) was run, yielding a W value of 0.983 and an associated probability of <0.855, and so the assumption that the statistical distribution is log normal cannot be rejected at the 1-percent-confidence level.

The area model, shown in a form suitable for computer simulation if so needed (that is, cumulatively, so that each data point has an explicit associated probability), is plotted in figure 3, along with the log-normal distribution as a line fitted to the data points. Values at 0.1, 0.5, and 0.9 probabilities (fig.

Table 1. Areas of cape- and ridge-associated marine sand deposits on the U.S. Atlantic Continental Shelf considered in this study.

[Letter preceding name denotes survey location in figure 1]

Nation and State	Area name	Reference
USDE	(a) Attached shoal field	McKenna and Ramsey (2002)
USFL	(b) Canaveral Shoal	Nocita and others (1990)
USMD	(c) Shoal F	Conkwright and Gast (1995)
USMD	(c) Shoal G	Conkwright and Gast (1995)
USMD	(c) Shoal H	Conkwright and Gast (1995)
USMD	(c) Shoal I	Conkwright and Gast (1995)
USMD	(c) Shoal J	Conkwright and Gast (1995)
USMD	(c) Shoal K	Conkwright and Gast (1995)
USMD	(c) Shoal L	Conkwright and Gast (1995)
USMD	(c) Shoal M	Conkwright and Gast (1995)
USMD	(d) Fenwick Shoal	Conkwright and others (2000)
USMD	(d) Isle of Wright Shoal	Conkwright and others (2000)
USMD	(d) Weaver Shoal	Conkwright and others (2000)
USMD	(e) Greater Gulf Bank	Conkwright and Williams (1996
USMD	(e) Little Gulf Bank	Conkwright and Williams (1996)
USMD	(e) Shoal B	Conkwright and Williams (1996)
USMD	(e) Shoal C	Conkwright and Williams (1996)
USMD	(e) Shoal D	Conkwright and Williams (1996)
USNC	(f) Area 1	Hoffman (1998); Boss and Hoffman (2001)
USNC	(f) Area 2	Hoffman (1998); Boss and Hoffman (2001)
USNC	(f) Area 3	Hoffman (1998); Boss and Hoffman (2001)
USNC	(f) Area 4	Hoffman (1998); Boss and Hoffman (2001)
USNJ	(g) Shoal A	Meisburger and Williams (1980)
USNJ	(g) Shoal B	Meisburger and Williams (1980)
USNJ	(g) Shoal C	Meisburger and Williams (1980)
USNJ	(g) Shoal D	Meisburger and Williams (1980)
USNJ	(g) Shoal E	Meisburger and Williams (1980)
USNJ	(g) Shoal F	Meisburger and Williams (1980)
USNJ	(g) Shoal G	Meisburger and Williams (1980)
USNJ	(g) Shoal H	Meisburger and Williams (1980)
USNJ	(g) Shoal I	Meisburger and Williams (1980)
USNJ	(g) Shoal J	Meisburger and Williams (1980)
USNJ	(g) Shoal K	Meisburger and Williams (1980)
USNJ	(g) Shoal L	Meisburger and Williams (1980)
USNJ	(g) Shoal M	Meisburger and Williams (1980)
USNJ	(g) Shoal N	Meisburger and Williams (1980)
USNJ	(h) BI–A	Meisburger and Williams (1982)
USNJ	(h) BI–B	Meisburger and Williams (1982)
USNJ	(h) BI–C	Meisburger and Williams (1982)
USNJ	(h) BI–D	Meisburger and Williams (1982)
USNJ	(h) BI–E	Meisburger and Williams (1982)
USNJ	(h) BI–F	Meisburger and Williams (1982)
USNJ	(h) BI–G	Meisburger and Williams (1982)
USNJ	(h) BI–H	Meisburger and Williams (1982)
USNJ	(h) BI–I	Meisburger and Williams (1982)
USNJ	(h) BI–J	Meisburger and Williams (1982)
USNJ	(h) BI–K	Meisburger and Williams (1982)
USNJ	(h) BI–L	Meisburger and Williams (1982)
USNJ	(h) BI–M	Meisburger and Williams (1982)
USNJ	(h) BI–N	Meisburger and Williams (1982)
USNJ	(h) BI–O	Meisburger and Williams (1982)
USNJ	(i) Avalon Shoal	Smith (1996)
USNJ	(i) Inner Sand Ridge	Smith (1996)
USSC	(j) Edisto Beach (Shoal)	Van Dolah and others (1998)
USSC	(j) Gaskin Bank	Van Dolah and others (1998)
USSC	(j) Hunting Island	Van Dolah and others (1998)
USSC	(j) Pawleys Island	Van Dolah and others (1998)
USSC	(j) Seabrook Island	Van Dolah and others (1998)
USSC	(k) Joiner Bank shoal	Wright and others (1999)
USVA	(l) Sandbridge Shoal	Maa and Hobbs (1998)

3) are from the statistical distribution. For example, the cape- and ridge-associated marine sand deposits represented by this distribution have a median area of 10 km^2—in other words, there is a 50-percent chance that a marine sand deposit will have an area of ≥10 km^2. Furthermore, there is a 90-percent chance that it will have an area of ≥1.7 km^2, and a 10-percent chance that it will have an area of ≥53 km^2. The mean area is substantially larger than the median of data for these cape- and ridge-associated sand deposits, or 22 km^2. The area model is particularly useful in visualizing how many undiscovered deposits are likely in a permissive tract. (See above description of part 3 of the approach of Singer, 1993.)

Several significant correlations are suggested between log-normal area and other variables in the dataset. However, no correlation was found between log-normal deposit area and mean grain sorting (r=0.14, n=21), where is r is the correlation coefficient and n is the number of observations with both variables. There is a negative correlation (at the 1-percent-confidence level) between log-normal area and mean grain size (r=–0.51, n=32), suggesting that deposits with a larger area may have a smaller mean grain size. One of the strongest positive correlations (at the 1-percent-confidence level) is between deposit area and volume (r=0.92, n=47). If the area of a recognized cape- and ridge-associated marine sand deposit is known, the volume can be estimated by using the equation

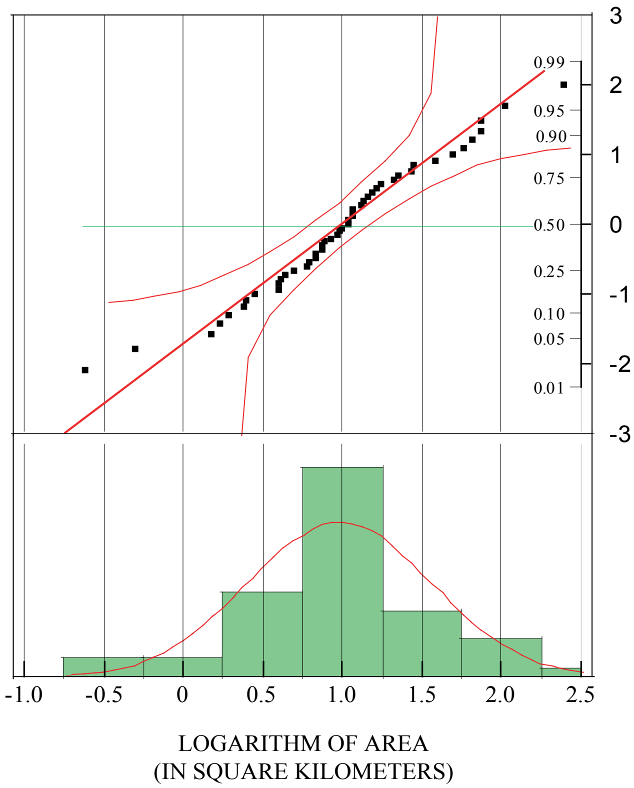

Figure 2. Histogram (lower part) and normal quantile-quantile plot (upper part) of area data for 47 of 54 cape- and ridge-associated marine sand deposits in survey areas (fig. 1). See appendix B and figure 13 for detailed discussion of format.

$$\log_{10} V = 0.43 + 0.855 \log_{10} A, \qquad (1)$$

where V is the volume (in millions of cubic meters) and A is the area (in square kilometers). In fact, 84 percent of the variation in deposit volume can be explained by knowledge of the deposit area, comparable to a regression model of onshore fluvial sand and gravel deposits (Bliss and Page, 1994).

Thickness Model

Thickness data are available for 34 of the 54 cape- and ridge-associated marine deposits in the study area (fig. 1). The dataset shows no pattern that fits a statistical distribution, and considerable uncertainty exists, given how this dataset was collected. The thicknesses of deposits along the coasts of North Carolina (n=4) and New Jersey (n=29) are not significantly different (χ^2=0.15, DF=1, p>χ^2=0.70). Available thickness data may facilitate determining whether the data from a target area indicate a possible undiscovered deposit.

Data on deposit thickness have similar limitations to those for deposit area. In addition, many thicknesses are measured from the top of first indication of sand to the bottom of the sampled core and do not represent the total thickness of sand in the deposits, and so the reported thicknesses are likely too small. Deposit thicknesses for cape- and ridge-associated marine sand deposits mostly range from 1 to 5 m in the dataset—a narrow range of only 4 m; the median thickness is 2.3 m.

Comparisons between thickness and the other variables in this study were by nonparametric methods, where ranks were substituted for values. Correlation between deposit thickness ranks and ranks of other variables was made by using Spearman's ρ, which is simply Pearson's r (or simply r,

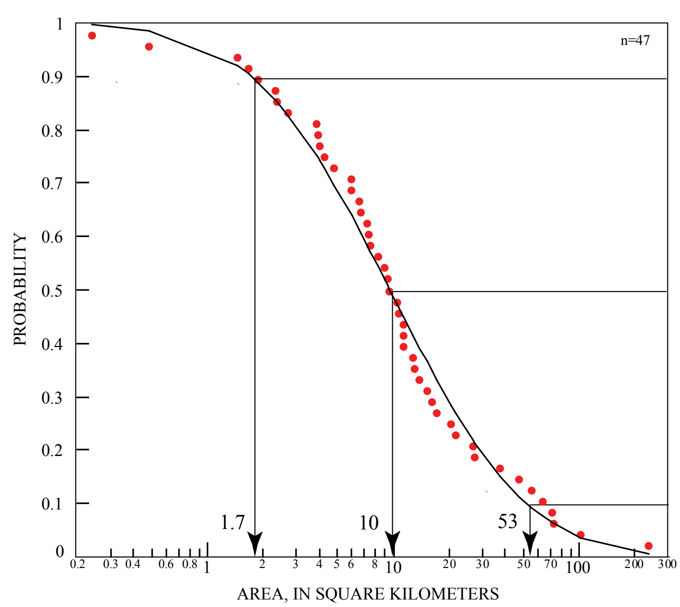

Figure 3. Area model of cape- and ridge-associated marine sand deposits.

Table 2. Phi (Φ) scale of grain sizes for sedimentary deposits

Grain size (mm)	Φ value	Size term (after Wentworth, 1922)
8.00–64.0	−3 to −6	Medium to very coarse pebbles
4.000–8.00	−2 to −3	Fine pebbles
2.000–4.000	−1 to −2	Very fine pebbles (includes granules)
1.000–2.000	0 to −1	Very coarse sand
0.250–1.000	1 to 0	Coarse sand
0.250–0.500	2 to 1	Medium sand
0.0313–0.125	3 to 2	Fine sand
0.0625–0.125	4 to 3	Very fine sand
0.0039–0.0625	8 to 4	Very fine to coarse silt
0.0010–0.0039	10 to 8	Clay

as used elsewhere in this report) calculated on the ranks and average ranks (Conover, 1999).

There is a positive and significant correlation between 33 deposits with both area ranks and thickness ranks (ρ=0.500, p>0.003) at the 1-percent-confidence level, suggesting that the larger the area, the thicker the deposit. There is also a positive significant correlation between 34 deposits with both volume ranks and thickness ranks (ρ=0.77, p>0.001), suggesting that the larger the volume, the thicker the deposit. No correlations were noted between 23 deposits with both thickness ranks and mean-grain-size ranks (ρ=−0.40, p>0.06), and between 11 deposits with both thickness ranks and grain-sorting ranks (ρ=−0.10, p>0.76).

Mean-Grain-Size Model

Data on mean grain sizes of sand are available for 36 of the 54 cape- and ridge-associated marine sand deposits in the study area (fig. 1). The mean grain sizes of deposits along the coasts of Maryland (n=13), and New Jersey (n=22) are not significantly different (χ^2=0.51, DF=1, $p>\chi^2$=0.47). The combined dataset may facilitate determining whether target areas (that is, possible undiscovered deposits) are comparable. As proposed by Krumbein (1934), model grain sizes are in Φ units, calculated as the negative logarithm (base 2) of the grain size (in millimeters). The result of the negative sign in the conversion is that as grain size decreases, Φ value increases. For example, for a grain size of 1 mm, Φ=0. Grain-size terms, grain sizes, and Φ values are summarized in table 2.

End-use requirements differ because the mean grain size and the variation in sand-grain distributions need to be comparable to those of the sand on those beaches where the material is expected to be used. The median Φ value of "mean grain size" in cape- and ridge-associated marine sand deposits is 1.5 (coarse sand), and the Φ value of the middle 80 percent of the grain-size distribution (that is, excluding the highest and lowest 10 percent of observations) ranges from 0.37 to 2.33 (fine to coarse sand).

As noted for the area model, mean grain size is inversely correlated with area and volume. There is no significant correlation between mean grain size and grain sorting (r=−0.31, n=24).

If the data (black squares, fig. 4) are normal, they are expected to group about the line. Recall that Φ units are logarithms to the base 2 and are transformed values by definition. The data points are also expected to fall within the Lilliefors confidence band (99-percent-confidence interval) bounded by the two curves on opposite sides of the diagonal. The patterns of data points on the Q–Q plot (upper part, fig. 4) does, indeed, suggest that the distribution may be log normal. To confirm this interpretation, a Shapiro-Wilk W test (Conover, 1999) was run, which gave a W value of 0.944 with an associated probability of <0.067, and so the assumption that the distribution is log normal cannot be rejected at the 1-percent-confidence level. Note that the break in data values between mean grain sizes of Φ~0.6 and Φ=1.1 is also evident in grain-size distributions in the sediment in many onshore rivers and streams. This break, which was first recognized in 1980, is commonly expressed as an abrupt transition from gravel- to sand-dominated streambeds (Parker, 1998).

The grain-size model, shown in a form suitable for computer simulation if so needed (fig. 5). (Recall that Φ value decreases as grain size increases.) Also shown in figure 5 is the log-normal distribution as a curve fitted to the data points. Values at 0.9, 0.5, and 0.1 probabilities are from the statistical distribution. Thus, there is a 90-percent chance that a marine sand deposit will have a grain size of Φ≤0.63, a 50-percent chance that it will have a grain size of Φ≤1.3, and a 10-percent chance it will have a grain size of Φ≤2.0. Nearly all the data points fall within these grain sizes.

Grain-Sorting Model

Data on grain sorting or standard deviation of Φ value (see preceding subsection; Boggs, 1995) are available for only 24 of the 54 cape- and ridge-associated marine sand deposits in the study area (fig. 1); all the data are from either Maryland or New Jersey. The grain sortings of deposits along the coasts of Maryland (*n*=13) and New Jersey (*n*=11) are significantly different (χ^2=7.11, DF=1, $p>\chi^2$=0.0077). Cape- and ridge-associated marine sand deposits along the New Jersey coast are more poorly sorted (median standard deviation of Φ value, 0.76) when compared to those along the Maryland coast (median standard deviation of Φ value, 0.55), making the model constructed here from combined data from both New Jersey and Maryland unsuitable for characterizing grain sorting in undiscovered deposits along either the Maryland or New Jersey coast. This model can be used in other coastal areas where data about grain sorting are unavailable or not significantly different from those used in the model.

Sediment samples with a standard deviation of Φ≤0.35 are identified as very well sorted, as defined by Boggs (1995)—in other words, the grain sizes in the sample are all nearly the same. As the standard deviation of Φ value increases, the range of grain sizes in the sample also increases. When the standard deviation of Φ value is >4, the sample is described as extremely poorly sorted (Boggs, 1995).

End-use requirements differ, but the grain sorting needs to be comparable to that in typical sand samples collected from the beaches where the material is expected to be used. The median standard deviation of Φ value for samples in this dataset is 0.63, or moderately well sorted (Boggs, 1995). In all, 90 percent of deposits have a grain sorting of Φ≤0.80, or moderately well sorted, and 10 percent of deposits have a grain sorting of Φ≤0.47, or well to extremely well sorted. None of the deposits has a standard deviation of Φ value >1, or poorly sorted.

As noted in previous discussions above, there is no correlation between grain sorting and area (*r*=0.14, *n*=21), thickness (*r*=–0.11, *n*=11), or mean grain size (*r*=–0.31, *n*=24). There also is no significant correlation between grain sorting and volume (*r*=–0.06, *n*=24).

If the distribution is log normal, the data points are expected to group about the curve and to fall within the Lilliefors confidence band (99-percent-confidence interval) bounded by the two curves on opposite sides of the diagonal. The pattern of data point on the Q–Q plot (upper part, fig. 6,) does, indeed, suggest that the distribution may be log normal. To confirm this interpretation, a Shapiro-Wilk *W* test (Conover, 1999) was run, which gave a *W* value of 0.979 with an associated probability of <0.87, and so the assumption that the distribution is normal (or log normal here) cannot be rejected at the 1-percent-confidence level.

The gravel-sorting model, shown in a form suitable for computer simulation if so needed (fig. 7). Also shown in figure 7 is the log-normal distribution as a line fitted to the data points. Φ values at 0.9, 0.5, and 0.1 probabilities are from the statistical distribution. Thus, there is a 90-percent chance that a marine sand deposit will have a grain sorting of Φ≥0.46, a 50-percent chance that it will have a grain sorting of Φ≥0.63, and a ≥10-percent chance that it will have a grain sorting of Φ≥0.81.

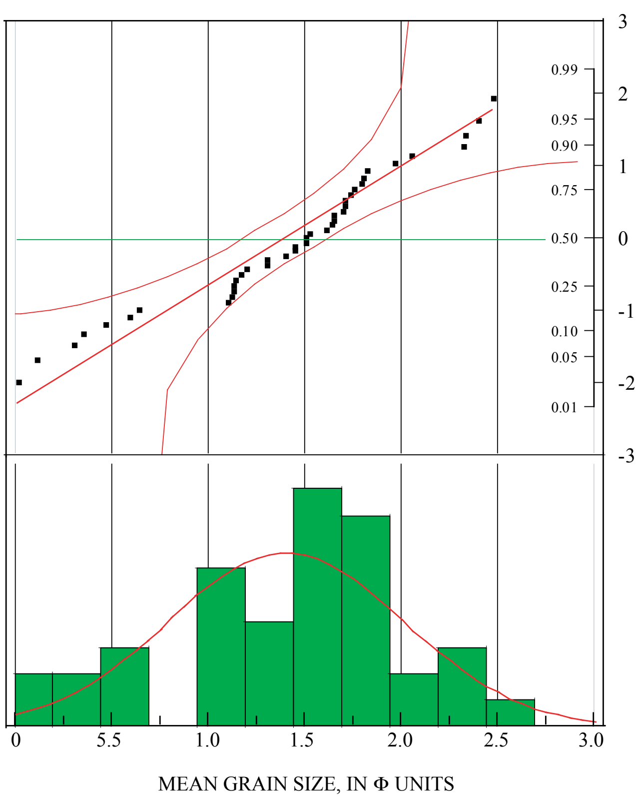

Figure 4. Histogram (lower part) and normal quantile-quantile plot (upper part) of mean-grain-size data for 36 of 54 cape- and ridge-associated marine sand deposits in survey areas (fig. 1). See appendix B and figure 13 for detailed discussion of format.

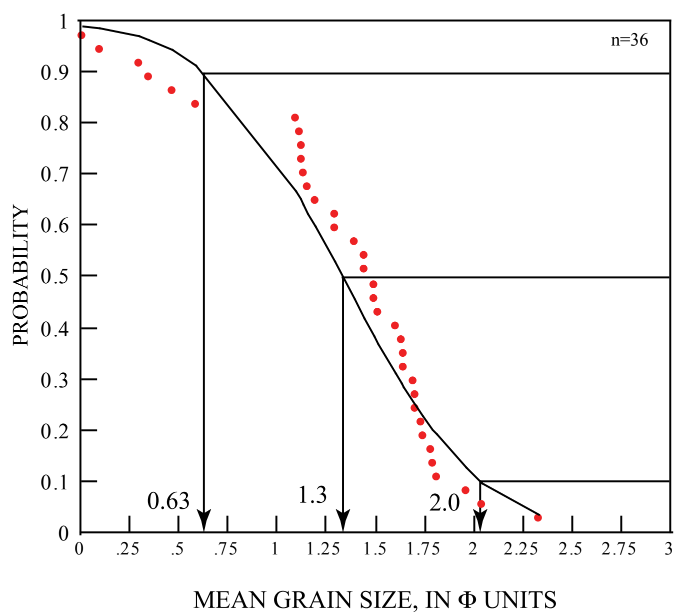

Figure 5. Mean-grain-size model of cape- and ridge-associated marine sand deposits.

Volume Model

Volume data were available for all 54 cape- and ridge-associated marine sand deposits in the study area (fig. 1). As noted previously, five of the six deposits in South Carolina appeared to have considerably smaller volumes. The volumes of deposits along the coasts of Maryland (n=17), North Carolina (n=4), New Jersey (n=31) and South Carolina (n=5) are significantly different (χ^2=17.2, DF=3, $p>\chi^2$=0.0006). The deposits in South Carolina have the lowest volume ranks as expressed by standardized scores and are clearly smaller than the other deposits in this study. Therefore, all the deposits in South Carolina were excluded in constructing the various models in this study. These six deposits may be members of a possible subpopulation of sediment-starved cape- and ridge-associated marine sand deposits or some other deposit type that needs to be separately modeled.

In contrast, the volumes of deposits along the coasts of Maryland (n=17), North Carolina (n=4), and New Jersey (n=31) are not significantly different (χ^2=5.4, DF=2, $p>\chi^2$=0.068). The combined data used in the volume model for

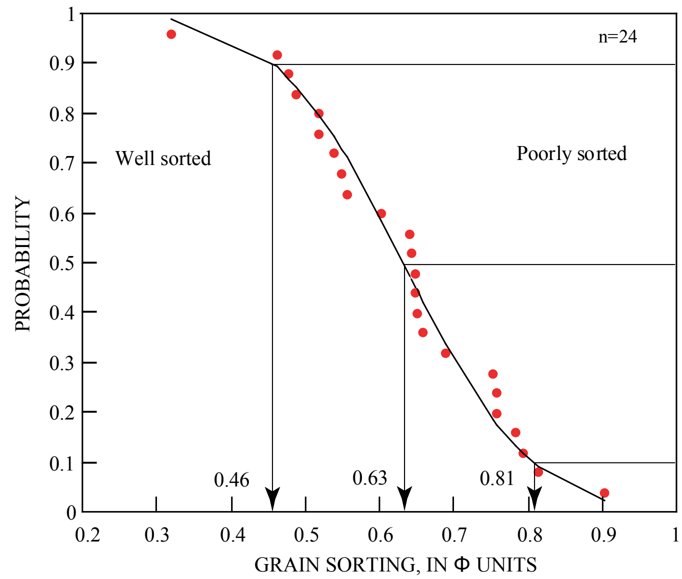

Figure 7. Grain-sorting model of cape- and ridge-associated marine sand deposits.

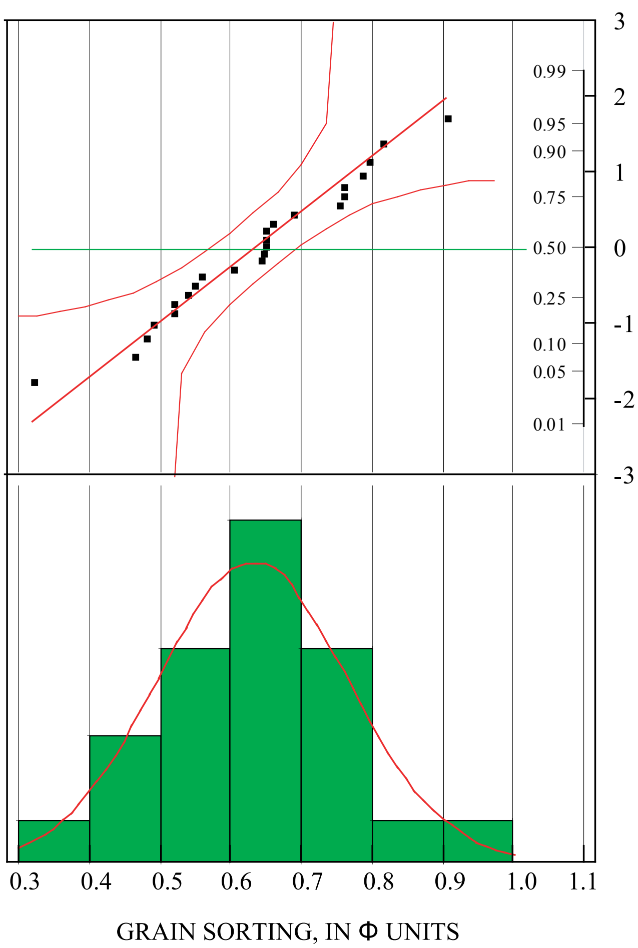

Figure 6. Histogram (lower part) and normal quantile-quantile plot (upper part) of grain sorting data for 24 of 54 cape- and ridge-associated marine sand deposits in survey areas (fig.1). See appendix B and figure 13 for detailed discussion of format.

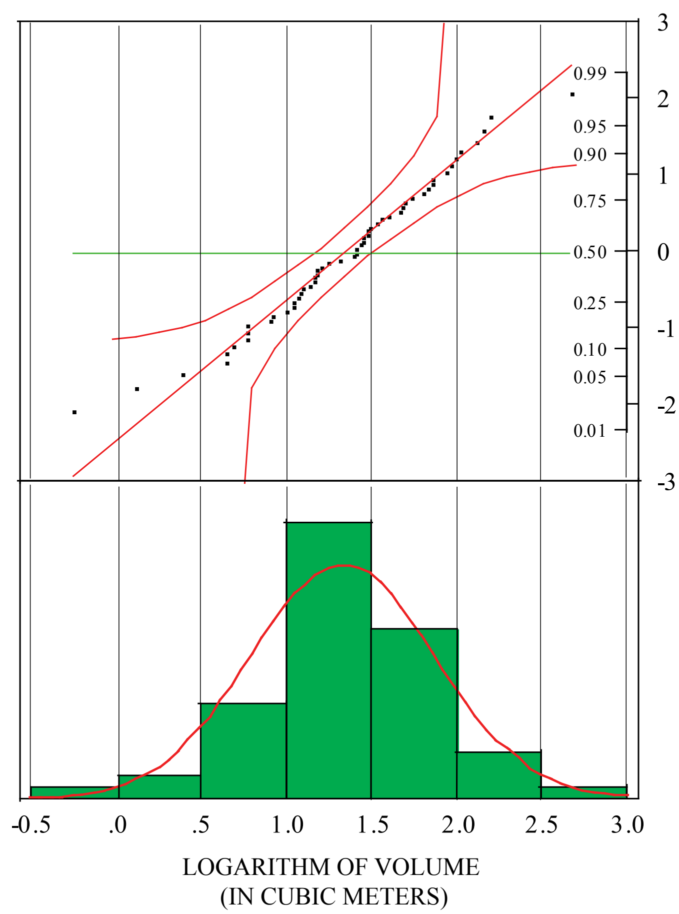

Figure 8. Histogram (lower part) and normal quantile-quantile plot (upper part) of volume data for 54 cape- and ridge-associated marine sand deposits in survey areas (fig. 1). See appendix B and figure 13 for detailed discussion of format.

all the other deposits are skewed, suggesting that the volumes (in millions of cubic meters) need to be transformed logarithmically. The transformed values for marine sand are plotted in figure 8. The data points are also expected to fall within the Lilliefors confidence band (99-percent-confidence interval) bounded by the two curves on opposite sides of the diagonal. The pattern of data points on the Q–Q plot (fig. 8) does, indeed, suggest that the distribution may be log normal. To confirm this interpretation, a Shapiro-Wilk *W* test (Conover, 1999) was run, which gave a *W* value of 0.959 with an associated probability of <0.104, and so the assumption that the distribution is normal (or log normal here) cannot be rejected at the 1-percent-confidence level. Correlations between volume and the other variables considered in this study have been previously discussed.

The volume model is in a form suitable for computer simulation if so needed (fig. 9). Also shown in figure 9 is the log-normal distribution as a line fitted to the data points. Values at 0.1, 0.5, and 0.9 probabilities (fig. 9) are from the statistical distribution. Thus, there is a 90-percent chance that a marine sand deposit will have a volume of ≥4.5 million m^3, a 50-percent chance that it will have a volume of ≥22 million m^3, and a 10-percent chance that it will have a volume of ≥110 million m^3. Half of the deposits have volumes of 11 to 52 million m^3, on the basis of quantiles (fig. 8). The volume model is used by the MCS program to estimate the volumes of undiscovered deposits, although this model is not particularly useful in estimating the probable number of undiscovered deposits because deposit volumes are more difficult to visualize during assessment than deposit areas, as discussed above.

Sand-Dominated-Facies Model

Cape- and ridge-associated marine sand deposits identified as sources of sand-size material commonly contain other materials (non-sand-dominated facies) either finer or coarser than sand. Therefore, the volume model presented above will generally overestimate the amount of sand suitable for use because volume data also are likely to include some silt and gravel. These less suitable materials are either interbedded or directly mixed with the sand. The sand content of marine sand deposits is less commonly reported, possibly owing to an underlying assumption that the nonsand fractions are minor by definition and that many deposits containing ≤100 volume percent sand are not reported and so may be missing from the dataset. For modeling purposes here, the 39 deposits with reported volumes but for which data on sand content are unavailable have been assigned a sand content of 100 volume percent. Thus, the sand-dominated-facies model presented here may be biased, and so its use in an MCS may lead to a slight overprediction of the amount of sand in undiscovered cape- and ridge-associated marine sand deposits. No comparisons were made among the sand deposits grouped by State for the sand-dominated-facies dataset.

Only 15 of the 54 cape- and ridge-associate marine sand deposits in the study area (fig. 1) had reported sand contents. All 54 deposits were used to construct a model in which 80 percent have either a reported or an assigned sand content of 100 volume percent. The resulting distribution of 11 deposits with sand-dominated facies of <100 volume percent is empirical (fig. 10) and cannot be tested in the same way as other variables. Unlike the other models, the model in figure 10 shows a distribution of sand-dominated facies for only 20 percent of the dataset. This type of distribution is also observed in several industrial-mineral-deposit types where high purity is sought and deposits are reported to have grades of 100 percent.

Comparisons between data on sand-dominated facies and other variables in this study were not made, given that 80 percent of the recorded sand contents are 100 volume percent and that 72 percent of these deposits in the dataset had their sand content assigned.

The sand-dominated-facies model, shown in a form suitable for computer simulation if needed (fig. 10), has a median

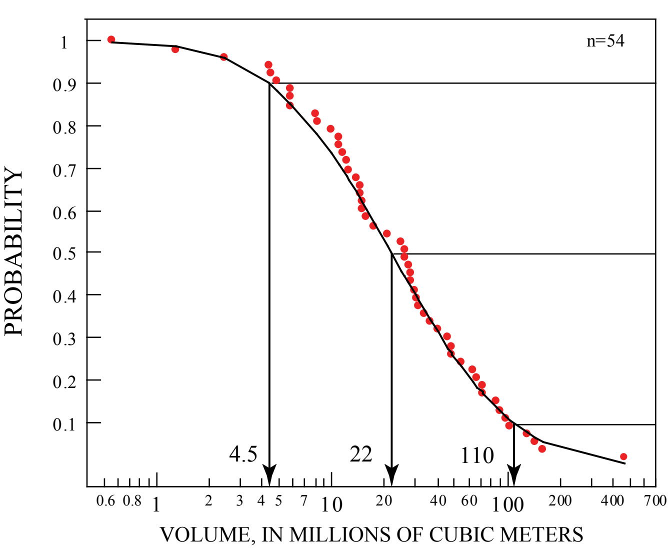

Figure 9. Volume model of cape- and ridge-associated marine sand deposits.

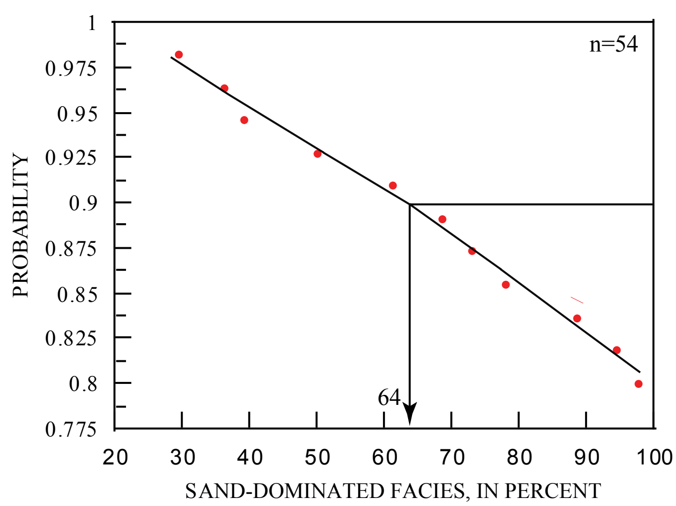

Figure 10. Sand-dominated-facies model of cape- and ridge-associated marine sand deposits. 42 of 54 deposits that are composed of 100 volume percent sand are not shown.

Table 3. Mineral-deposit density (MDD value) of cape- and ridge-associated marine sand deposits in three survey areas (fig. 1).

[MDD values in number of deposits per 1,000 km^2]

Survey area (fig. 1)	Area (km^2)	MDD	Reference
Maryland Shoal Field I–III	944	17.0	Conkwright and Grast (1995), Conkwright and Williams (1996a).
Cape May, N.J.	1,235	14.6	Meisburger and Williams (1980b).
Offshore Nags Head, Kitty Hawk, and Kill Devils Hills, N.C.	640	9.4	Hoffman (1998).

sand content of 100 volume percent. Thus, there is a 90-percent chance that a marine sand deposit will contain ≥64 volume percent sand, and a 10-percent chance that it will contain 100 volume percent sand.

Spatial-Density Model

Spatial-density models of mineral deposits suitable for mineral-resource assessment are a relatively new undertaking in quantitative mineral-deposit modeling. They are particularly useful in meeting the requirement of part 3 of Singer's (1993) approach described above; however, they are but one of about a half-dozen guidelines that are suitable for subjectively estimating the probable number of undiscovered deposits (Singer, 2007, table 1). An estimate of the probable number of undiscovered deposits is a key input variable needed to run the MCS. Instead of subjectively estimating the probable number of undiscovered deposits, a type of spatial model can also be used. The spatial model can also be used as a guide to subjective estimation if desirable. Called a mineral-deposit-density (MDD) model, it is simply the number of deposits per some standard unit of area (generally reported as number of deposits per 1,000 km^2) in a well-explored area. Like an assessment tract, all of the area is permissible. Construction of a spatial-density model requires the deposits to be defined in the same way as for other quantitative models. An important purpose of the MDD model is to allow for an independent estimate of the probable number of undiscovered deposits for assessment purposes. Research in MDD modeling began in the 1980s (Bliss and others, 1987; Bliss and Menzie, 1993), and a final report that summarizes most of this effort, as well as the results of new investigations, was published by Singer and others (2001). Typical MDD values for both metallic- and industrial-mineral deposits range from 1 to 10 deposits per 1,000 km^2; the full range of MDD values is from 0.01 to 100 deposits per 1,000 km^2. In a recently completed, new interim MDD model for one type of onshore sand and gravel deposits in a resource assessment of Afghanistan, MDD values in six areas range from 0.1 to 1.0 sand and gravel deposit per 1,000 km^2 (Bliss and Bolm, 2007).

We used three studies of areas with cape- and ridge-associated marine sand deposits to calculate three MDD values for three survey areas (fig. 1; table 3). These values should be used carefully because these survey areas were selected not for their absence but for their presence of marine sand deposits! Thus, the three survey areas can be expected to have higher MDD values than if they have been selected at random within some predefined area permissive for marine sand deposits. The boundaries of the survey areas were not set by geologic conditions but were arbitrarily selected by those conducting the survey and so are likely nested within a much larger area permissive for cape- and ridge-associated marine sand deposits. These MDD values should be used as a guide to estimating the probable number of undiscovered deposits, with an understanding that they may be too high for some parts of permissive tracts for cape- and ridge-associated marine sand deposits.

Estimating the Number of Undiscovered Deposits

Perhaps no task in mineral-resource assessment is perceived to be more challenging than that of subjectively estimating of the probable number of undiscovered deposits. However, such a task must be undertaken by an assessment team if an MCS is to be run and a probabilistic distribution of marine sand resources is to be provided. An important requirement is that the characteristics of the undiscovered deposits be comparable to all the characteristics in the models described above. Therefore, nearly all the undiscovered deposits are expected to have volumes of >1 million m^3 (fig. 8).

Several tools are available to help in making these estimates, including spatial-density models as described above. A common approach to estimating the probable number of undiscovered deposits is to assemble an assessment team. Estimates are to be made cumulatively at three probabilities:

Table 4. Probable number of undiscovered marine sand deposits estimated by three assessment-team members for a hypothetical assessment tract.

Level of estimate	Assessment-team members			Consensuses
	A	B	C	
90-percent chance of at least:	1	1	2	1
50-percent chance of at least:	1	2	4	2
10-percent chance of at least:	2	5	8	4

0.9 (most likely), 0.5, and 0.1 (least likely). In an example of a hypothetical assessment area somewhere on a continental shelf (table 4), three assessment-team members have provided independent estimates of the numbers of undiscovered cape- and ridge-associated marine sand deposits. In this example, assessment team member A is pessimistic about the number of undiscovered deposits, while member C is optimistic. Team member A believes that there is a good chance of at least one deposit but that there is also is no more than a 50-percent chance of at least one deposit. All three estimators, however, are fairly certain that there is at least one undiscovered deposit, although assessment-team member C believes that there is a 90-percent chance of at least two deposits. To achieve consensus, each assessment-team member needs to present arguments and evidence in support of his estimate. The consensus is not necessarily an average but represents an agreement among the assessment-team members. Singer (2007) noted that assessment-team estimates are likely to be better than those provided by individual estimators.

How do assessment team members make these estimates and reach a consensus? What type of evidence do they use? Singer (2007, table 1) presented six techniques used by past assessment teams to estimate the probable numbers of undiscovered deposits, albeit almost all past assessments involve estimating the probable number of undiscovered metallic-mineral deposits on shore. In some assessments (Menzie and Singer, 1990), individual occurrences, prospects, and other indications of mineralization of a specific deposit type are assigned individual probabilities, and the results are combined. Each assessment-team member notes the similarity of a given target to known mineral deposits of the type under assessment and his estimate is based on that experience. Has the area been well explored? If not, then the evidence for a target may suggest the presence of an undiscovered deposit. Better assessment-team members are those with a long involvement both in the mineral-deposit type under evaluation and in the areas being assessed. Using the frequency of deposits in well-explored areas (or MDD models described previously), both published and from experience, can help guide the estimates.

In our estimate of marine sand resources, evidence of undiscovered deposits would be suggested by geologic setting as described by various remote-sensing and geophysical methods, bathymetric geomorphology, grain-size data, and other site-specific features. The assessment team may evaluate all of these characteristics in making its estimates and later suggest why one set of arguments for a specific set of estimates of the number of undiscovered deposits is more compelling than another. Well-explored parts of an assessment area should not be forgotten during these discussions. Again, assessment-team members need to recall that all undiscovered deposits are expected to have characteristics that fall somewhere within the range of values—that is, at least half of the undiscovered deposits would have volumes larger than the median in the volume model (fig. 9) described above.

Assessment teams also need to understand that MSC results will be more sensitive to the grade-and-tonnage model (or volume model in this application) than to small errors in the estimate of the probable number of undiscovered deposits (Singer, 2007). Therefore, the selection of appropriate marine-sand-deposit types by the assessment team is most important.

Setting Up the MCS, Using Marine-Sand-Assessment Data

The MCS method provides a probabilistic estimate of marine sand resources within permissive tracts. The overall structure of the MCS program (fig. 11) and its results follow the procedure outlined by Root and others (1992), which includes using 4,999 iterations in the simulation. The simulation values for presentation were calculated with the JMP software, a statistical package (SAS Institute, Inc., 2002).

In the hypothetical MCS exercise that follows, two distribution models are used to predict resource values for cape- and ridge-associated marine sand deposits: (1) deposit volume and (2) sand content, together with an estimate of the probable number of undiscovered deposits, using the consensus values listed in table 4 and summarized in table 5. In this hypothetical example, the empirical option is used so that unrealistically large values of grade and tonnage are avoided. The values are selected from the data used and not from the statistical distribution that can be used to describe the data. However, the piecewise linear-distribution approximation used by Root and others (1992) was not used. Instead,

Table 5. Probabilities of numbers of undiscovered marine sand deposits estimated for a hypothetical assessment tract.

Level of estimate	Expressed as	Consensuses
90-percent chance of at least:	*N*(0.9)	1
50-percent chance of at least:	*N*(0.5)	2
10-percent chance of at least:	*N*(0.1)	4

the data values used to construct the models were directly mapped onto a uniform distribution where each variable was assigned an equal discrete probability range.

Executing the MCS Program

Step 1. How many cape- and ridge-associated marine sand deposits are present?—Within each of the 4,999 iterations, the MCS program also executes between zero and four subiterations to estimate the probable number of undiscovered deposits within each iteration selected by the program (table 6), using the product of the allocation procedure and the empirical option described by Root and others (1992) and the estimates listed in table 5. The probable number of undiscovered deposits follows a default distribution guided by the three probability estimates listed in table 4. Values between these three estimates are selected so that they are "approximately in the middle of all possible choices" as graphically and mathematically presented by Root and others (1992, p. 130–131, fig. 4).

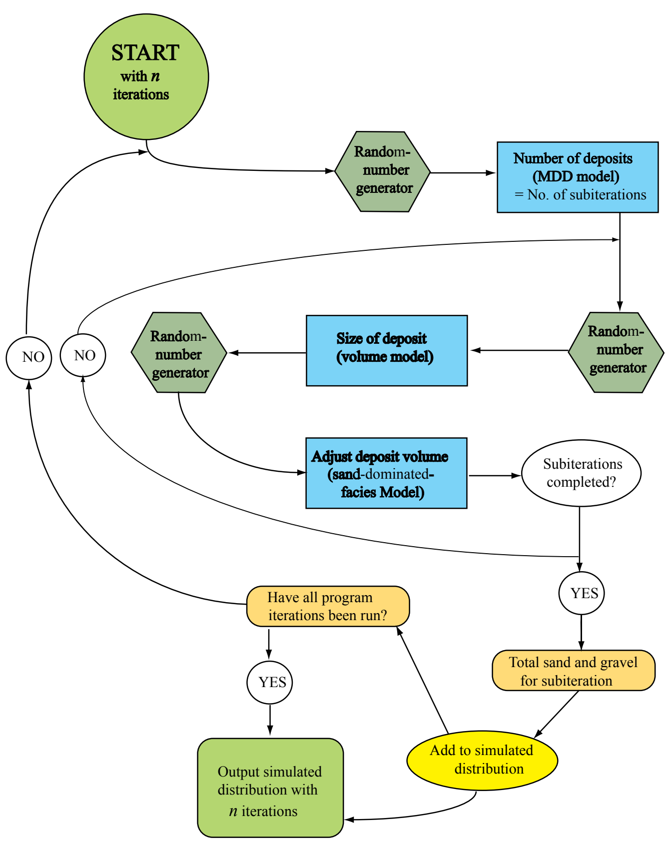

Figure 11. Schematic flowchart illustrating overall structure of Monte Carlo simulation program.

Step 2. What is the volume of each cape- and ridge-associated marine sand deposit?—Given one or more deposits within a specific iteration, each deposit is assigned a volume by using the volume model (fig. 9). Random numbers between 0 and 1 generated by the program are used to select corresponding volumes in the volume model. With the empirical option as used here, the reported values are used directly in the MCS and not the fitted statistical distribution, so that each of the 54 deposit volumes is assumed to be equally likely, and the chance of selection is equally divided among all 54 values. Therefore, all the volumes in the model are equally likely, whereby there is 1 chance in 54 of selection during the MCS, or a probability of 0.0185 (1/54). For example, if the random number generated is exactly 0.5, the volume selected for the deposit is 22 million m^3, or the median volume. The program as described in this section is executed for all the deposits described in step 1, and volumes are selected by the program for all deposits predicted to be present per iteration. In this example, the first iteration includes three deposits, and so three volumes are selected for each of the three subiterations.

Table 6. Default distribution of undiscovered marine sand deposits and probabilities used in a Monte Carlo simulation.

Default number of deposits	Probability
0	0.067
1	0.233
2	0.3
3	0.2
4	0.2

Step 3. What proportion of each cape- and ridge-associated marine sand deposit is actually sand?—The sand content of each simulated deposit is determined by using the data in the sand-dominated-facies model (fig. 10). The selection process is similar to that used in step 2, where the

empirical option is used. Of the 54 marine sand deposits in the study area (fig. 1), slightly fewer than 80 percent have either reported or assigned values of 100 volume percent. For the rest of the data, each of the 11 values other than 100 percent volume in the sand-dominated-facies model is assumed to be equally likely, and so the chance of selection is equally divided among all 11 values, or 1.8 percent (1/54). For example, if the random number generated is 0.1, sand content is selected to be 100 volume percent, multiplied by the volume selected from the volume model. In this example, the deposit volume is not reduced. All three volumes in the first iteration are modified in this step, if needed.

Step 4. Determine whether all deposits predicted in the iteration have been created, compute a total volume, and output the results after 4,999 iterations have been executed.—In the first iteration, the final volumes of the three deposits are summed and transferred to the output dataset. The resulting dataset, after all 4,999 iterations have been run, is then transferred to the JMP program for analysis, and the result is reported as a cumulative probability distribution (fig. 12) for the cape- and ridge-associated marine sand deposits calculated by the MCS, which is the expected distribution of undiscovered deposits in the assessment area. There is a 90-percent chance that the assessment area contains ≥5.0 million m^3 of marine sand, a 50-percent chance that it contains ≥59 million m^3 of marine sand, and a 10-percent chance that it contains ≥200 million m^3 of marine sand. The mean volume of sand predicted is 93 million m^3. As noted in the section above entitled "Introduction," ~920 million m^3 of marine sand has been extracted and used since the 1920s. The mean volume of undiscovered marine sand in this hypothetical assessment is 93 million m^3, or 10 percent of the volume of marine sand used in the past 80 years in the United States.

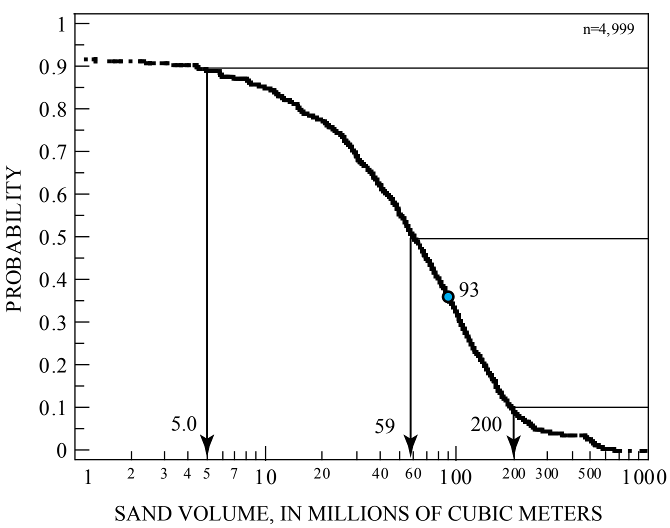

Figure. 12. Cumulative distribution of predicted sand resources in cape- and ridge-associated sand deposits in a hypothetical survey area (fig. 1). Blue dot, mean estimated resource of 93 million m^3 of sand.

Summary

Quantitative mineral-resource assessment is now possible for one type of marine sand deposit—cape- and ridge-associated marine sand deposits. We have presented a set of models that can be used to screen data from target areas that are suspected to contain undiscovered deposits. Using the number of targets observed plus guidance provided by several preliminary MDD models, the probable number of undiscovered deposits can be subjectively estimated. These estimates are to be made in areas that have seabed geomorphology, marine conditions, and other evidence that suggesting that this specific deposit type may be present. With estimates of the probable number of undiscovered deposits available, an MCS can be run with those values plus the distribution of values in two new models that describe the volume and proportion of sand-dominated facies typical of cape- and ridge-associated marine sand deposits. The MCS produces a cumulative probabilistic distribution of sand resources yet to be discovered—information of interest to marine-sand users both private and public, economists, and continental-shelf-resource managers.

Conclusions

Production of material from marine sand deposits is likely to be limited by various economic and environmental factors, including maximum water depth, end-use criteria, and conditions dictated in State and Federal regulations not explicitly considered but that may have played a part in estimating the probable number of undiscovered deposits. For example, current U.S. dredging equipment suitable for extracting offshore sand is suitable to work in depths no greater than ~40 m; however, extraction at this depth is unlikely because the maximum depth at which marine sand can be extracted economically is 30 m along the U.S. Atlantic coast. Another important factor that can restrict or eliminate development of sand resources is that their locations are preemptively used to meet other government and economic needs, as described in the descriptive model (see app. A).

Another concern is that marine sand deposits containing >10 volume percent mud and clay or ≥10 volume percent gravel are unlikely to be suitable sources of sand for beach replenishment or other uses. Some deposits in the dataset used to construct models contain considerably more that 10 volume percent nonsand facies materials, albeit dredging procedures may still permit exclusion of these undesirable materials. The most suitable sand has a grain-size distribution (texture and sorting) comparable to that of the native beach where is to be used. Recreational users in the United States prefer sand beaches that are white (Leatherman, 1997), and this statement may be true elsewhere in world, including New Zealand, where "lighter sand colours [are] generally preferred" (Dahm, 2002, p. ii).

One unusual characteristic of marine sand deposits in comparison with most terrestrial mineral deposits (except some fluvial-channel sand and gravel deposits) is their capacity to recover, given that they are in a dynamically maintained state. Some marine sand deposits have undergone repeated dredging, followed by recovery of the shoal at the same site (Hayes and Nairn, 2004). Therefore, some marine sand deposits may be considered a renewable resource. However, little monitoring and postdredging surveying is routinely done on dredge borrowsites, and much is unknown about how marine sand bodies form, evolve, and interact with adjacent sea-floor sediment.

Assessing potential mineral resources is an important function provided by geologists and others in government. Considerable care needs to be taken to ensure that the assessment is internally consistent. For example, in this assessment and the subsequent MCS, the predicted sand resources are only those expected to occur in cape- and ridge-associated marine sand deposits. The sources in all other types of marine sand deposits (for example, blanket deposits, channel fill, ebb- and flood-tidal deltas) are beyond the scope of this report.

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Appendix A. An Interim Descriptive Model for Cape- and Ridge-Associated Marine Sand Deposits

By S. Jeffress Williams and James D. Bliss

Introduction

Descriptive models allow users to classify mineral deposits into types for use during a mineral-resource assessment. As noted by Barton (1993, p. 8), "a mineral deposit model is a systematically arranged body of information that describes some or all of the essential characteristics of a particular feature or phenomenon; it presents an idealized condition within which essential elements may be distinguished and from which extraneous elements may be recognized and excluded." The following descriptive model provides an interim guide to help users recognize cape- and ridge-associated marine sand deposits as applied to the mineral-resource assessment of the U.S. Atlantic Continental Shelf. Construction of descriptive models like those of Cox and Singer (1986) for marine sand deposits has never before been attempted. This interim model is expected to be replaced by one or more improved descriptive models of marine sand deposits suitable for use in future mineral-resource assessments of marine aggregate resources.

Most marine sand deposits occur in the depositional system within which they are created or dynamically maintained. Therefore, parts of the genetic model, including tides, currents, wave intensities, and river discharges, are directly observable. Other evidence for the presence of the marine sand deposits is obtained from associated marine sedimentary deposits and sea-floor bathymetry, generally of Holocene age. Some Pleistocene deposits in deeper water may no longer be associated with their genetic processes. Some genetic processes are local and directly related to deposit formation (currents, tidal strength), whereas others are regional, including some that occur inland or along the edge between the marine and terrestrial setting, such as those that also form beaches.

Most of the information in the literature describing cape- and ridge-associated marine sand deposits is not about that part of these bedforms suitable as a source of sand for extraction but about the capes and sand ridges as recognizable bathymetric feature. Surveys of marine sand deposits reveal that much of the material present in sand-ridge fields, specifically in ridges, is unsuitable for economic use. Some sand bodies are inadequate in thickness or area, or both, to justify extraction; in other places, the sand characteristics (for example, grain size, sorting) are incompatible with expected end uses. The expected proportion of the area underlain by sand deposits within survey areas of marine sand-ridge fields may be as small as 16 percent. In addition, a few of the sand deposits described as possible sources of marine sand contain considerable amounts of silt-size material (see subsection above entitled "Sand-Dominated-Facies Model").

Although the quantitative models presented above consider only deposits found on the U.S. Atlantic Continental Shelf, this descriptive model includes deposits on sand ridges in marine areas of Canada, the United Kingdom, the Netherlands, Japan, Korea, China, and the Mediterranean Sea. Recognition and classification of sea-floor sand ridges for the purpose of probabilistic assessment has just begun, and proper classification of associated sand deposits is still unclear. Inclusion of possible deposits of the type under assessment outside the study area (fig. 1) helps users understand that this deposit type is likely present in other similar marine settings, and helps develop a broader perspective on these deposits and the possible locations of associated undiscovered sand resources.

The following descriptive model provides information predominantly about cape- and ridge-associated deposits, the hosts for the sand bodies in which most marine sand deposits consistent with the quantitative models occur, and not about the contained sand deposits.

Brief Description

Deposit synonyms: Regularly to irregularly spaced linear ridges that become curved at the mouths of estuaries and embayments; ridges may be either attached to or detached from onshore beaches and barrier island systems.

Principal commodities produced: Sand-size rounded grains; deeper water deposits may be coarser (Goff and others, 2005).

Byproducts (*other commodities*): Gravel.

End uses (*of produced commodities*): Beach nourishment, coastal and wetland restoration, and shore protection.

Typical deposits: See table 1 for deposits on the upper U.S. Atlantic coast and Continental Shelf; see also Sable Island Bank, Nova Scotia, Canada (Hayes and Nairn, 2004).

Relative importance of deposit type (*the proportion of the world supply of the produced commodity supplied by this deposit type*): Unknown but important for areas along the U.S. Atlantic Continental Shelf and more limited parts of the Gulf of Mexico.

Associated/related deposit types (*other deposit types spatially or genetically associated with this deposit type*): Marine sand and gravel deposits of various types; ilmenite beach deposits.

Regional and Local Geologic Attributes

Tectonic-margin type: Trailing edge.

Coastal classification: Transgressive, with mixed-energy wave-dominated marine environment coupled with barrier islands cut by migrating tidal-inlet systems (McBride and Moslow, 1991). Mesotidal (mean range, 2–4 m) areas like those in parts of the North Sea may be permissive; a sand deposit does not form on prograding delta fronts or macrotidal coasts (mean range, >4 m).

Continental-shelf properties: Wide sandy continental shelf; numerous bathymetric irregularities.

Coastal terrestrial features: Barrier-island chains with inlets (McBride and Moslow, 1991); absence of large sediment-loaded rivers with large deltas; estuaries with capes and spits at mouth; extensive sand beaches; headlands may be present and related to ridge formation (Dyer and Huntley, 1999).

Coastal marine and associated processes:

(a) Sources of sand: Transgressive seas rework terrestrial sand or sand-and-gravel deposits, both fluvial and glacial, and onshore beach and dune deposits; delivery of fluvial sand and gravel is ongoing but insufficient to allow delta formation; shoreline erosion of bedrock and headlands.

(b) Processes developing sand deposits: Wave-dominated, tide-dominated, or mixed wave- and tide-dominated (McBride and Moslow, 1991) longshore currents; ridges in all tidal seas with current velocities >0.5 m/s, given a sand source (Dyer and Huntley, 1999); formation as detached ridges for shorefaces of barrier islands and maintained by currents, either tide or storm driven (Hayes and Nairn, 2004). Deposition related to irregularities on the sea floor, including abandonment of ebb-tidal delta deposits with inlet migration (McBride and Moslow, 1991); tidal currents drive circulation of sand both around and over ridges (Dyer and Huntley, 1999).

(c) Preservation and repositioning of sand deposits: Longshore currents result in ridge migration; sand waves are present on active ridges; relief increases with water depth (Harrison and others, 2003); upward refraction of waves up along detached sand-ridge sides. These processes result in sand transport over ridge crest and maintain ridges after detachment (Hayes and Nairn, 2004); migration of ridges may accelerate during storms.

(d) Degradation, modification, and destruction of sand deposits: Moribund ridges in the Mediterranean Sea are 95 to 110 m deep (Bassetti and others, 2006). At 50-m depth, ridges are no longer active on the U.S. Atlantic Continental Shelf (Goff and others, 2005); absence of large sand waves on flanks; round crested cross; slope of ≤1º; sandy or muddy swales (Dyer and Huntley, 1999); possibly coarse older and moribund deposits (Goff and others, 2005).

Age range: Holocene; Pleistocene in deeper water (Berné and others, 2002); latest Pleistocene (11,900–11,600 ka in the Gulf of Lions, Mediterranean Sea; Bassetti and others, 2006).

Water depth: Nearshore areas; including ridges expressed as shoals attached to beaches and barrier islands to possible maximum depth of 90 m on the U.S. Atlantic Continental Shelf; possibly as deep as 110 m in the Mediterranean Sea if those occurrences belong to this deposit type.

Sea-floor bathymetry: Linear ridges parallel to predominate wave-approach direction; open shelf and at estuary entrances with and without recession (Dyer and Huntley, 1999); typically observed in extensive regions of asymmetric ridges or shoals bounded by both steep (6º) and shallow (≤1º) slopes (Dyer and Huntley, 1999); contorted cape associated ridges; maximum length, 80 km, average width, 13 km; average height, tens of meters; ridge spacing proportional to width (Dyer and Huntley, 1999), increasing with water depth (Off, 1963) in the Maryland sector: 3.7 to 12.1 km long, mostly 8.3 to 13.9 km long; 0.9 to 2.8 km wide, mostly 1.4 to 2.3 km wide (Duane and others, 1972; Swift and Field, 1981); in the Korea Strait: maximum 63 km long, 3 to 9 km wide, and 22 m thick (Park and others, 2003).

Related geomorphologic feature(s): Areas between active ridges with clean gravel (Dyer and Huntley, 1999).

Associated sediment(s): Silt, gravelly silt; sandy silt, gravelly sand; clay-size material; interridge areas separated by swales of clean gravel (Dyer and Huntley, 1999).

Sand-deposit mineralogy: Sand-size quartz, other durable and chemically inert minerals sought for use; colors, grain shape.

Impurity mineralogy/materials: Clay and clay-size minerals, organic and shell debris, gravel, silt, carbonates.

Typical sand deposit dimensions: See "Sea-Floor Bathymetry" item above for ridges hosting marine sand deposits; see text for sand-deposit thicknesses and areas.

Maximum limitation of overburden: Unknown but dependent on dredging equipment used.

Exploration data source(s): Vibracore, age determination; fossil assemblages.

Geochemical signature(s): None known at present.

Geophysical signature(s): Chirp seismic; seismic; side-scan sonar.

Other exploration guide(s): Sand-ridge spacing increases with water depth. False positives include superficially appearing sand-ridge deposits that are erosional features where they are composed of fine sediment (deltaic, estuarine materials) as observed in deep (90 m) water in the East China Sea (Berné and others, 2002); erosional ridges also observed in Cretaceous sediment along the west coast of Long Island, N.Y.

Most readily ascertainable regional attribute: Barrier islands with inlets along coastal zones, with lengths measured in hundreds of kilometers.

Most readily ascertainable local attribute: Possibly exposed as a shoal at or near the water surface or within ridge fields readily recognized from bathymetry.

Economic Limitations

Physical/chemical properties affecting minability/use: Mean grain size and sorting of sand in sand deposit is best if compatible with the beach on which it is to be used; contamination with clay, silt, and coarse sediment is undesirable; grains should be rounded or possibly uneven in dependence on application.

Compositional/mechanical processing and other restrictions: Maximum dredge equipment depth, 40 m; maximum economic depth of extraction, 30 m (U.S. Atlantic Continental Shelf).

Preemptive-use limitations: Marine sand deposits of this type are common and of greatest utility as resources in nearshore parts of the Continental Shelf, and so also commonly in promising locations with many other uses: vessel navigation, pipelines, drilling platforms, cables, military and homeland security facilities, wind farms, and other related activities. These sand bodies too commonly serve as valuable marine benthic habitats and may be characterized as Essential Fish Habitats and off limits to such activities as dredging. These uses will commonly preclude the use of all or significant parts of these sand deposits as a resource.

Distance to transportation, processing, and end use: The U.S. Army Corps of Engineers estimates dredging and transport costs of marine sand at \$4.00/yd^3 (\$5.20/m^3) within 1 mi (1.6 km) of the U.S. Atlantic coast, with each additional mile adding \$1.00/yd^3 (\$1.30/m^3) to a maximum distance of 5 miles (8 km) (Weggel, in Leatherman, 1989), the maximum possible distance for a floating-pipe dredge system. Beyond this distance, sand is dredged and transported by hopper dredge or by barge, then by truck, to location at an additional cost of \$2.00/yd^3 (\$3.00/m^3). The final cost of dredged sand is largely determined by transportation distance. Material containing >10 volume percent clay or gravel is likely unsuitable for use as beach nourishment.

Spatial properties important in exploration and exploitation: Sand-ridge geometry changes from long and thin (length-to-width ratio, 9:1) in shallow water to short and thick (length-to-width ratio, 3:1) in deeper water (≥15 m) (Swift and Field, 1981). Note that this specification applies to the full ridge and may not be applicable to the contained sand deposits that may be suitable for extraction.

Environmental/health concerns related to deposit type (*asbestosis, silicosis; other environmental problems; types and extent of ecologic disruption*): Until about 2004, most sand extraction was from deposits in 5- to 15-m-deep water and at depths at which associated physical and biologic impacts are expected to be greatest (Hayes and Nairn, 2004). Dredging can disrupt bottom ecosystems, create turbulence, and permanently modify sea-floor geometry, affecting currents, and may also result in remobilization of buried or sequestered industrial waste.

Appendix B. Statistical Methods and Diagrams

One way to test data collected for modeling is by determining whether the values can be treated as random samples drawn from a single population. Data from mineral deposits of the same type commonly include variables (volume, area) that can be described by using either a log-normal or a normal distribution. Statistical rejection of these distributions may suggest that some of the deposits are misclassified or that errors related to data reporting or collection exist. Testing of data in this way is important in screening processes during modeling, as illustrated in figure 13, which plots the same dataset expressed in two different ways. The values in the histogram shown in green in the lower part of the figure are also the same values shown as data points in the upper part of the figure. The upper part of the figure is called a normal quantile-quantile (Q–Q) plot. These figures help explore how well the normal distribution describes the data. The normal distribution is expected to have a symmetrical, bell-shaped curve, as shown by the red line on the histogram in the lower part of the figure. The distribution is described by using two variables: the mean and the standard deviation. The mean is the value at the peak of the curve, and the standard deviation describes how values are distributed about the mean; thus, the larger the standard deviation, the greater the spread in values, and the broader the bell mouth. The normal distribution also can be expressed as a "standard normal distribution," where the value of the mean is set to 0 and the standard deviation is set to 1 with values both positive and negative. These values are also called a normal score, as given along the right vertical axis of the Q–Q plot. The normal distribution, when scaled as a standard normal distribution, produces a straight line, as shown in the upper part of the figure (the same red line shown overlaying the histogram in the lower part of the figure). The black data points are expected to fall near the line if they can be described by using a normal distribution. If the data points fall outside the Lilliefors confidence boundaries located above and below the normal-distribution curve in the Q–Q plot, this result suggests that the assumption of a normal distribution would be rejected at the one-percent-confidence level. Note that the probability scale adjacent to the normal score also has values so distributed as to accommodate a bell-shaped shown as a straight line, and lists the probabilities in increasing order. See standard statistics textbooks for more information about the widely used normal distribution.

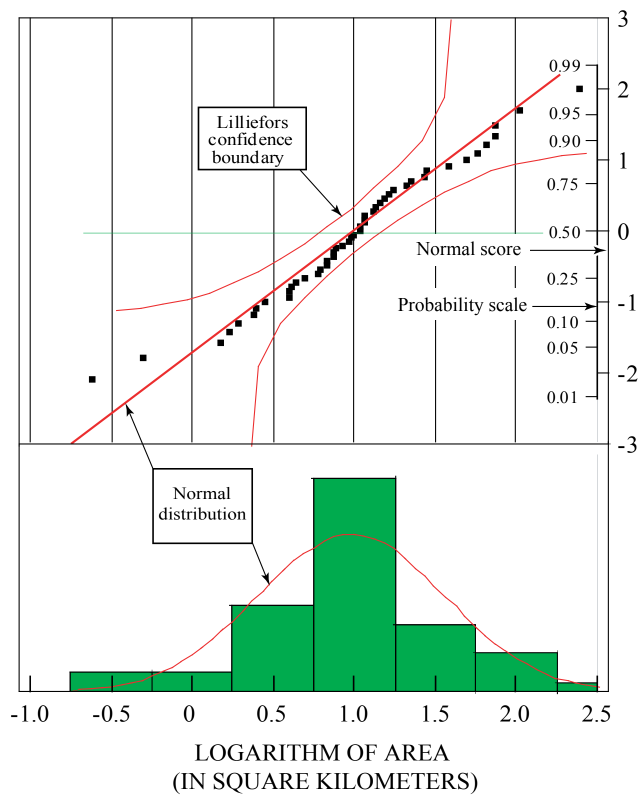

Figure 13. Same histogram (lower part) and normal quantile-quantile (Q–Q) plot (upper part) for 47 of 54 cape- and ridge-associated marine sand deposits as in figure 2, with normal-distribution curves and Lilliefors confidence boundary indicated.