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Evaluating Continental Shelf Seabed-Elevation Changes from Archived Sediment-Core Records: Issues with Vertical Positioning and Implications for Integration with Subsurface Geophysics

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ABSTRACT

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Sediment-core records from the sand ridge–dominated inner continental shelf of Delaware were studied to address impacts of seabed morphodynamics and positioning accuracy on data integration. Differences in vertical seafloor position were calculated for 366 point locations from core-report information (from 1984 to 2017) and a 2007 echo-sounding data set. Resulting net-change metrics were evaluated against seafloor geology and shelf zonation based on morphology. While gravelly units trended slightly towards net-elevation loss at an average of –0.2 m, shoal sand bodies averaged net-zero change. Almost 90% of change metrics fell within ±2 m, approximating the average relief of major shelf bed forms. A pairwise analysis of variance test revealed no statistically significant difference in vertical change at the 0.05 confidence level, based on geology, nor based on shelf zonation. Vertical positioning inaccuracies and reporting issues are primary concerns, even after quality control eliminated over 20% of available core records (total $n = 466$) because of undocumented tidal correction and vertical datum conversion procedures, which could have resulted in vertical offsets on the order of 2 m. Within the remaining data set, questionable values were recognized by a GIS-based buffer analysis, using core age and an assumed 10 m/y rate of bed-form migration to isolate metrics in disagreement with seafloor morphology. Data from three coring projects consistently overvalued net-change predictions, raising questions about their utility as stratigraphic benchmarks for ground-truthing seismic data. Accurate constraint of core depth is crucial for offshore resource allocation and infrastructure planning efforts, highlighting the importance of investigating vertical data resolution and addressing reporting inaccuracies.

ADDITIONAL INDEX WORDS: *U.S. Mid-Atlantic, inner continental shelf, subsurface data integration, water depth, core elevation.*

INTRODUCTION

Understanding continental shelf stratigraphy and morphodynamics has direct economic implications for offshore infrastructure projects (*e.g.,* windfarm and cable installation) and resource analysis (*e.g.,* sand assessment). Beach replenishment in Delaware, which helps to promote the state's annual coastal tourism intake of over $500 million (McKenna and Ramsey, 2010), for example, relies almost exclusively on material from offshore sand ridges. The mapping of available sand resources on the shelf requires the integration of core information (*e.g.,* sediment texture and stratigraphic picks) and geophysical data (*e.g.,* seismic reflection). Together, they provide the spatial constraints for volume models based on select sediment-texture criteria. Marine mapping projects have amassed large lithologic and geophysical data sets along the U.S. Atlantic margin over the last decades, and stratigraphic models are continuously being refined as new data become available. However, uncertainties accompany the integration of these time-transgressive data sets, the impacts of which on geologic interpretations remain to be addressed in full. Above all, the question of how seafloor morphodynamics (*e.g.,* migration of sand ridges and corresponding changes in seafloor elevation) and vertical positioning accuracies factor into core-seismic data integration and resource assessment needs to be more distinctly evaluated. This study analyzed a large, multidecadal data set consisting of sediment-core records from the inner continental shelf of Delaware in order to address vertical data control and establish whether spatial information from core reports can offer insight into seafloor morphodynamics. The stratigraphic implications of this "big-data" analysis approach are discussed, particularly as they relate to seismic-core data integration and resource assessment.

Background

The integration of core and seismic-reflection imagery has been foundational to offshore stratigraphic mapping (Belknap and Kraft, 1985; Belknap, Kraft, and Dunn, 1994; Kraft and Belknap, 1986; Williams, 1999) and resource-allocation efforts (Finkl *et al.*, 1997; McKenna and Ramsey, 2010; Williams *et al.*, 2012). Models of surface geology and paleogeography, while providing a basis for understanding late Holocene coastal development, are static and offer little information on modern

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seafloor morphodynamics. However, surficial investigations of the seafloor and subsurface models are complementary, because bathymetric constraint is needed for stratigraphic assessment, while the subsurface may influence seafloor morphodynamics. Given the mobility of sand ridges, the integration of subsurface data sets collected decades apart (*e.g.,* using old core data to ground-truth interpretations of new seismic-reflection imagery) can mislead correlation efforts.

Much of what is known about shelf morphodynamics is based on marine acoustic surveying (*e.g.,* high-resolution multibeam sonar), which has facilitated process-driven investigations of the continental shelf seafloor (Brothers *et al*., 2013; Hughes Clarke, Mayer, and Wells, 1996; McBride and Moslow, 1991; Pendleton *et al*., 2017). Digital images of seafloor texture (at submeter resolutions) allow current directions and strengths to be inferred from bed-form morphology, establishing direct linkages between hydrodynamics and bed-form size and pattern (Coleman *et al*., 1981; Parsons *et al*., 2005). On a larger scale, sand-ridge migration trends have been studied along many parts of the storm-dominated U.S. Atlantic coastal margin, including the Nova Scotia shelf (Li and King, 2007), Long Island shelf (Nnafie *et al*., 2014), New Jersey shelf (Goff *et al*., 1999), and portions of the Mid- to south Atlantic shelves (Trowbridge, 1995). Resurveying localities before and after major storms has also allowed researchers to quantify morphologic change at the event scale (Durán *et al*., 2018; DuVal, Trembanis, and Skarke, 2016; Hughes Clarke, 2012; Pendleton *et al*., 2017; Simarro *et al*., 2015). In an effort to study the impacts of Hurricane Sandy on shelf-sediment mobility, Trembanis *et al*. (2013) employed acoustic mapping techniques to monitor the seabed off Delaware's Atlantic coastline. Wave ripples of around 1 m in wavelength were resolved after the storm at depths >25 m, where none had been seen prior to the storm. Hurricane Sandy's offshore geomorphic legacy was also investigated from pre- and poststorm geophysical data sets from the nearby New York shelf, providing insight into storm hydrodynamics (Arora *et al*., 2018; Goff *et al*., 2015; Schwab *et al*., 2017; Warner *et al*., 2017). While marine geophysical studies are rapidly advancing our knowledge of process-form interactions over the short-term, decadal morphodynamics and implications for stratigraphic assessment are not well constrained.

Decadal morphodynamic trends are not easily deciphered (let alone quantified) across continental shelves, in part due to decreasing data quality and coverage with age. Improved constraint of vertical change over decadal time spans is needed to help bridge the gap between process-based geomorphic studies and stratigraphic framework models (*i.e*. models of Quaternary coastal evolution). The decadal time frame should be an important consideration to offshore infrastructure design (*e.g.,* windfarms) and sand-resource assessment, particularly considering predictions of future sea-level rise (DeConto and Pollard, 2016; Domingues *et al*., 2008) and hurricane frequency and severity (Bender *et al*., 2010; Webster *et al*., 2005). Sediment vibracores have been collected for decades along the Atlantic seaboard for sand resource-allocation purposes, offering an opportunity to examine their usefulness in addressing shelf morphodynamics and issues of vertical data constraint. While prior studies have characterized bathymetric changes using time-separated echo-sounding surveys (Schimel *et al*., 2015; Schmitt *et al*., 2008), the utility of archived core information in addressing changes in seafloor position has yet to be thoroughly explored. The Delaware Geological Survey (DGS) actively maintains an offshore core database, which provides access to sediment descriptions, photographs, textural data, and information on coring conditions, including water depth at time of collection. These data are accessed for geologic mapping purposes, offshore sand inventorying, and stratigraphic modeling (McKenna and Ramsey, 2010; Ramsey and Tomlinson, 2011, 2012). The inner continental shelf of Delaware is particularly well suited for this analysis because of the high data density and tight stratigraphic constraint provided by numerous investigations (Belknap and Kraft, 1985; Belknap, Kraft, and Dunn, 1994; Kraft and Belknap, 1986; Williams, 1999). Work on sand-ridge morphology and migration patterns along the inner Maryland and southernmost Delaware shelves also offers insights into regional sedimentary dynamics and general bed-form migration patterns (Pendleton *et al*., 2017; Swift and Field, 1981).

Two primary questions drove this investigation: Do large offshore core data sets contain useful information on shelf morphodynamics? What are the implications of vertical data constraint on core-seismic data integration for offshore resource assessment?

Study Area

Data coverage spans the length of Delaware's N-S–trending, 40-km-long Atlantic barrier coastline and extends 15 km offshore (Figure 1). Prevailing littoral currents along most of the Delaware shore flow northwards (towards Cape Henlopen). A nodal zone (approximately at Bethany Beach) separates these currents from southward littoral flow (McKenna and Ramsey, 2010). Mean tidal range is approximately 1.25 m, and the inner continental shelf is compartmentalized into distinct morphologic zones (Figure 1b). The shoreface environment connects to the inner shelf platform, a high-relief area of attached and detached shoal fields. Water depths are generally less than 15 m, and the region is typified by shore-oblique sand ridges that range up to 4 km in length, trend NE-SW, are spaced hundreds of meters apart, and have trough-to-crest height differentials between 2 m and 4 m. The outer shelf platform, largely located in federal government waters (beyond 5 km from shore), has less relief (*i.e*. fewer bed forms) and is marked by a steady offshore increase in water depth from 15 m to 20 m (within the confines of the study area). Two topographically prominent sand bodies stand out: (1) the Hen and Chickens Shoal (HCS), and (2) the Fenwick Shoal Field (FSF; Figure 1b). The former is a 10-km-long, SE-trending, shore-attached sand body of around 1 km in width. It is characterized by relief of up to 8 m and parallels the late Pleistocene Delaware River paleovalley, situated beneath the modern Delaware River ebb-tidal delta channel (Belknap and Kraft, 1985; Childers, 2014; Kraft, 1971; McKenna and Ramsey, 2002; Twitchell, Knebel, and Folger, 1977). The FSF is a shore-detached feature located around 10 km seaward of Little Assawoman Bay (Figure 1b). Its spatial extent is on the order of 20 km^2, and water depths across its apex are as shallow as 6 m; total shoal body relief is on the order of 12 m.

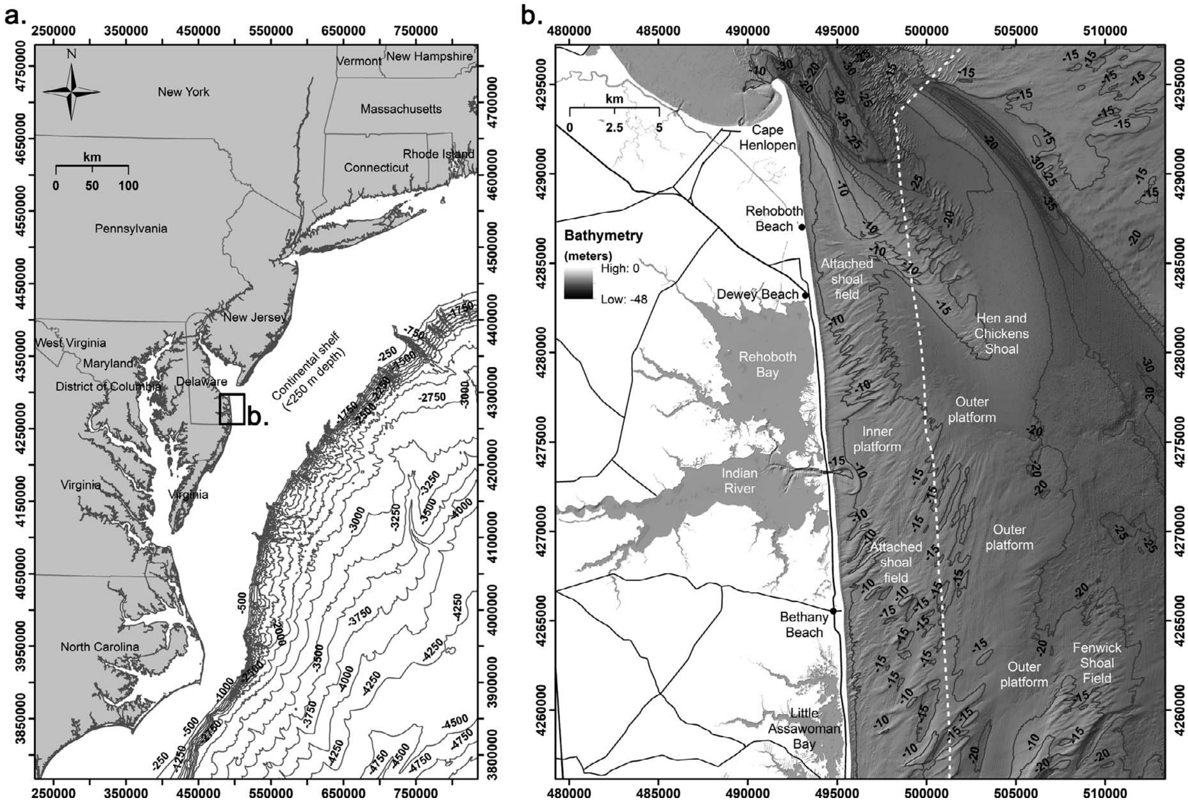


Figure 1. Maps showing: (a) the location of the study area with respect to the Mid-Atlantic coastal margin; and (b) bathymetry of the study area, highlighting major morphologic compartments of the Delaware inner continental shelf. All bathymetry contours are in meters (contour intervals are 250 m and 5 m, respectively). Estuarine water bodies and the locations of beach towns (used for reference) are labeled in part b, and elevation data are derived from a 2015 USGS 1 m DEM, based on 2007 NOAA hydrographic survey data sets 11647, 11648, 11649, and 11650.

METHODS

This investigation made use of geologic and bathymetric information from the DGS core database and a U.S. Geological Survey (USGS)/National Oceanic and Atmospheric Administration (NOAA) bathymetric data set, respectively. Vertical change metrics were calculated from these data and compared against geospatial variables, including surface geology (*i.e.* the distribution of muddy, sandy, and gravelly units at the seafloor).

Data Set

Information on 466 offshore vibracores was incorporated into this analysis (Figure 2). This information stemmed from many different sources, including federal agencies such as the U.S. Army Corps of Engineers (USACE) and the Bureau of Ocean Energy Management (BOEM), state agencies such as the Delaware Department of Natural Resources and Environmental Conservation (DNREC) and the Maryland Geological Survey (MGS), and University of Delaware (UD) theses and dissertations (Table 1). The spatiotemporal distribution of core data is highly irregular, and locations often cluster by project (and thus age), as suitability studies for potential sand-borrow sites were generally limited in scope (*e.g.,* ACOE2011 project; Figure 2). Temporal data distribution is skewed towards the modern, and spatial trends in data coverage exist. Only 119 cores predate 1997, and not many of these were collected seaward of the inner shelf platform (*i.e.* in federal waters). Data from the 1980s (58 cores) are confined to the foreshore (<10 m depth) and nearshore (<15 m depth) environments; cores collected in 1997 (84 cores), on the other hand, are widely dispersed across the study area (Figure 2). Most coring projects of the last decade (since 2008) focused on sand-resource potentials in areas along the ~5 km (3 mile) offshore (state-federal government) boundary, offering high spatial data densities along the 15 m bathymetric contour.

One-hundred cores were omitted from the net-vertical change analysis due to insufficient documentation of the way in which core depths were established (Table 1). Data for change analysis included only core locations that offered the following information: (1) type of equipment used to assess water depth (*e.g.,* echo-sounder) and horizontal positioning (with uncertainty estimates), (2) tide-correction procedures, and (3) vertical datum. Survey reports from the 2000s onward consistently included this information. Quality assurance/quality control (QA/QC) was performed on older reports to assess whether information meeting these criteria could be obtained. In cases where tide corrections had not been implemented, but positioning was otherwise well supported, the documented time of coring was used to create correction

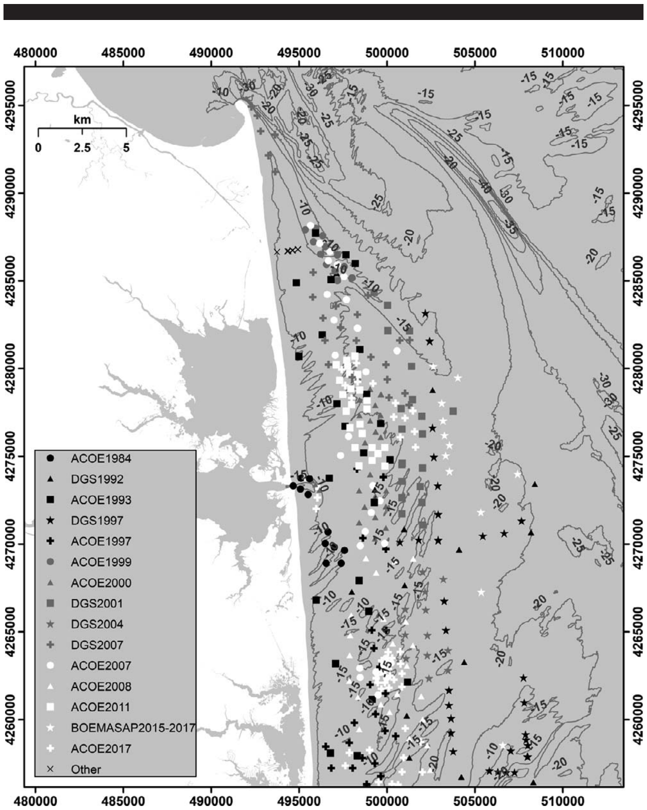


Figure 2. Map showing DGS core coverage, coded by project. Specifics are listed in Table 1. This figure depicts the cumulative data set, consisting of survey information accessed for geologic mapping. A subset of these points was used in geomorphic assessment.

factors using data from NOAA Tide Station 8557380 in Lewes, Delaware. Reports providing depth values in the National Geodetic Vertical Datum of 1929 (NGVD29), mean low water (MLW), or mean lower low water (MLLW) datum types were converted to North American Vertical Datum of 1988 (NAVD88), in adherence to current standards and the bathymetric digital elevation model (DEM; Pendleton *et al.*, 2015), using NOAA's VDatum 3.9 software. In cases where coring project reports failed to provide information on vertical datum and/or if tidal correction procedures went undocumented, data were omitted from further analysis (Table 1). Vertical uncertainties would have otherwise approached the relief of most of the shoal fields in the study area (Pendleton *et al.*, 2015, 2017), based on a maximum tidal range of 1.5 m and differences between datum types on the order of 0.8 m (Figure 1b).

Data-Management and Mapping Procedures

Location information (x, y, z coordinates) and stratigraphic surface picks were exported from DGS databases and imported into ESRI's ArcMap 10.6 for management, processing, evaluation, and illustration purposes. A USGS digital seafloor bathymetry model, based on 2007 NOAA hydrography data sets (survey ID files 11647–11649; Pendleton *et al.*, 2015), provided the temporal benchmark for quantification of vertical change in seafloor position from datum-normalized core elevations. Elevations in 2007 were extracted from DEM raster pixel values by coring location, providing a pairing of values for each data point. Differences in NAVD88 seafloor elevation between time of coring, as documented in coring reports (*i.e.* the DGS archives), and 2007 (as sampled from the USGS bathymetric DEM) were calculated and evaluated in the context of geospatial variables (*e.g.,* surface geology).

A metric of anticipated maximum vertical change was derived based on core age and a hypothetical rate of bed-form migration (of 10 m/y), based on maxima reported in echo-sounding studies along the Delmarva Peninsula by Pendleton *et al.* (2017). The age differential between core and echo-sounding data sets was multiplied by this rate to produce a radius value for DEM-raster extraction based on spatial buffer analysis. This was based on the rationale that longer time frames will produce larger potential for change to occur due to bed-form migration (as a function of time and distance; Figure 3). Maximum and minimum pixel values (of elevation) were extracted from the USGS DEM from the buffer areas and compared against the computed vertical net-change metric, accordingly. This was done, in part, to identify data points beyond the range of probable net-change values (based on 2007 seafloor morphology) and help with identification of potential project-specific vertical offsets (*i.e.* consistent over/underestimation of vertical change by project).

Statistics

Statistical analyses were performed on the data using R version 3.3.2. The following parameters were investigated as independent controls on seafloor-elevation changes: (1) surface geology (based on the uppermost core interval), (2) time (*i.e.* the difference between year of coring and 2007; Figure 3), and (3) original water depth (at $t = 0$). Pairwise analyses of variance (ANOVAs) were used to assess the potential for differences based on these variables. Individual pairwise comparisons were evaluated using *post-hoc* Tukey's honest significant difference (HSD) tests. All groups within these tests met assumptions of normally distributed residuals and homogeneous variances at the 0.05 level, as determined by Levene's test. Surface geology, reduced to distributions of sandy, muddy, and gravelly units (Figure 4), was investigated as an independent control on seafloor geomorphology, given established relationships between grain diameter and the critical condition for incipient motion of sediment (Graf, 1984). Prior work has addressed grain-size variations across continental shelves in the context of hydrodynamic regimes and geomorphology (McNinch, 2004; Murray and Thieler, 2004).

Time was investigated as the independent variable, allowing geologic processes to unfold, whether gradually or by (the accumulation of) punctuated, high-energy events (*e.g.,* Hurricane Sandy). The morphologic compartmentalization of the shelf prompted an evaluation of the data set by depth bin (*e.g.,* 0–10 m *vs*. 10–20 m), given established relationships between water depth and grain-movement thresholds under oscillatory wave and associated current conditions (Clifton, 1976; Goldsmith *et al.*, 1974; Komar and Miller, 1973). Regions situated close to shore, where water depths are <10 m (approximating the depth of closure; Kraus, Larson, and Wise, 1998; Nicholls *et al.*, 1998), should be more highly impacted by littoral processes than areas of greater water depth.

Table 1. *Information on cumulative core data set, grouped by project code and analytical use.*

		Project Code	Year	Area of Coverage	No. Cores
Geologic mapping of seafloor	Unknown vertical datum and tide correction	SDK1970	1970	State and federal waters	9
		ACOE1976	1975	Finger shoals and proximal Hen and Chickens	11
		—	1980	Indian River inlet	3
		DNREC1981	1981	Nearshore along entire Delaware coast	36
		—	1985	Little Assawoman Bay	1
		—	1986	Little Assawoman Bay	1
		—	1986	Little Assawoman Bay	5
		—	1988	Fenwick shoals	1
		—	1992	Indian River inlet ebb tidal shoal	1
		—	1992	Indian River inlet	1
		DGS97MMTC	1997	Federal waters	22
		—	1997	Fenwick shoals	5
		—	2011	Rehoboth Beach	4
	NAVD88 datum, used in net-change analysis	ACOE1984	1984	Indian River inlet and Bethany Beach	11
		DGS92	1992	Entire offshore	14
		ACOE1993	1993	Rehoboth Bay to off Indian River inlet	24
		—	1995	Hen and Chickens shoal	1
		ACOE1997	1997	Bethany Beach to Fenwick Island	22
		DGS97Alpine	1997	Federal waters	35
		ACOE1999	1999	Hen and Chickens shoal	15
		ACOE2000	2000	Rehoboth Bay to off Indian River inlet	30
		DGS01	2001	Dewey Beach south to off Indian River inlet	24
		DGS04	2004	Bethany Beach	13
		DGS07	2007	Cape Henlopen south to off Rehoboth Bay	26
		ACOE2007	2007	Off entire coast	33
		ACOE2008	2008	Bethany Beach south to off Fenwick Island	23
		ACOE2011	2011	Rehoboth Beach	24
		BOEMASAP	2015	Rehoboth Beach and Fenwick	6
		BOEMASAP	2016	Rehoboth Beach and Fenwick	4
		BOEMASAP	2017	Rehoboth Beach	3
		—	2016	Rehoboth Beach	13
		ACOE2017	2017	Entire offshore	45

RESULTS

Seafloor elevations at two different points in time are recorded for 366 point locations across the inner continental shelf of Delaware (Figure 5a). One common temporal data point is provided by the 2007 echo-sounding data set (Pendleton *et al.*, 2015), which serves as the baseline for evaluating vertical changes from core elevations. Older elevation values were subtracted from younger in all instances, so that negative vertical change would reflect a net loss with time, while positive vertical change would express gain. The following analyses take elevation metrics at face value, while the discussion addresses vertical uncertainties and the implications thereof. Values are rounded to the nearest decimeter, which is consistent with the order of magnitude in vertical accuracy based on echo-sounding data (Pendleton *et al.*, 2015).

The average vertical change in position based on all data points (*i.e.* the arithmetic mean) approximates zero (–0.03 m). In total, 211 data point locations measure elevation losses (of up to 6 m), 134 data points are affiliated with elevation gains (of up to 5.4 m), and 21 data points show no discernible vertical change (Figure 5). Around 87% of the vertical change metrics fall within ±2 m, and all but two outliers (the minimum and maximum values reported above) are confined to ±4 m (Figure 5b). The overall median value is –0.2 m, with Q_1 and Q_3 confining the middle half of the distribution to –2.3 m to 1.9 m, respectively. Some coring projects inferred greater vertical change than others. ACOE 1997 and ACOE2011 are associated with vertical median differentials in excess of +2 m (Figure 5c).

Vertical change was evaluated with respect to dominant lithotypes (*e.g.,* sandy *vs*. muddy sediments; Figure 6a) and coring depth (Figure 6b), where the latter served as proxy for morphologic zone and relative association to wave base. Predominantly sandy surface units collectively comprise the bulk of the data set ($n = 287$), while only 44 cores sampled muddy deposits at the surface. While for sandy surface units, this metric ranged from –6 m to +5.4 m (with a median value of –0.1 m and mean value of zero), gravel metrics ranged from –1.9 m to +2.8 m (with a median value of –0.4 m and mean of –0.2 m). The sand-data outliers (both from the ACOE2017 survey) are well beyond the bed-form relief of the area.

Water depths at time of coring were compared against metrics of vertical change. Three depth bins were used in this analysis: <10 m, 10–15 m, and >15 m (Figure 6b), corresponding to the broad morphologic compartmentalization of the Delaware inner shelf (Figure 1b). Water depths <10 m correspond to the nearshore area, where most attached and detached (high-amplitude) shoal fields are situated (along with the proximal HCS). The inner shelf platform, which houses lower-amplitude sandy bed forms (of sheet sands), primarily occupies depths between 10 m and 15 m, while the outer platform (beyond 15 m in depth) is the least topographically varied. While net-change range values are comparable, data appear to become more slightly skewed towards overall net erosion from the outer shelf towards the nearshore, as reflected in median change values of 0, –0.2 m, and –0.4 m in the onshore direction, with associated n values of 123, 187, and 56, correspondingly (Figure 6b).

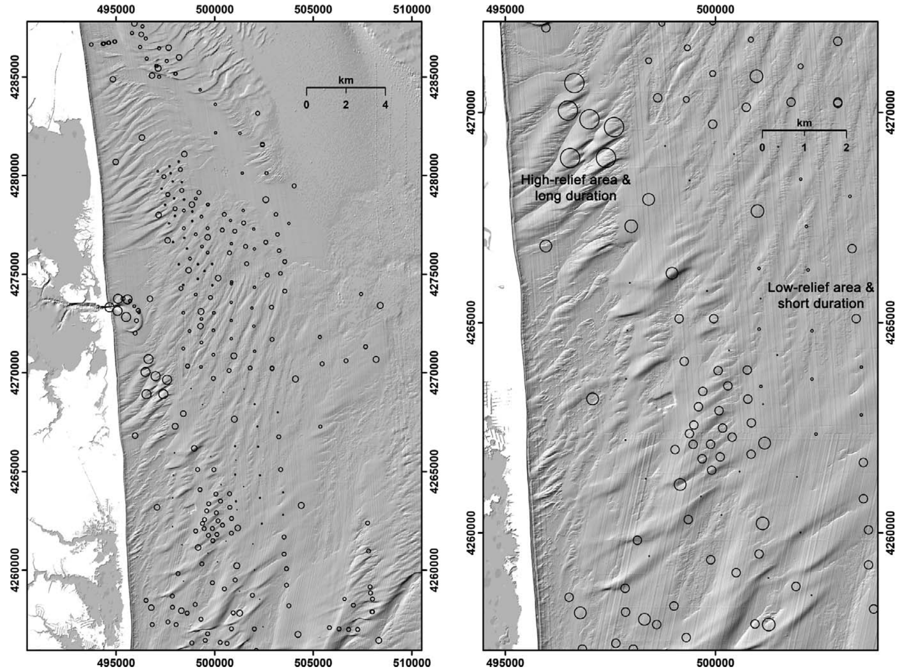


Figure 3. Shaded relief map of the study area showing data points buffered by age (in years) multiplied by a presumed maximum rate of sand ridge migration of 10 m/y (based on prior work by Pendleton *et al.*, 2017). Two areas are highlighted showing different ends of the spectrum in terms of potential magnitude of change as a function of time (size of the buffer) and seafloor topography (*i.e.* slope). Cores collected in 2007 (the vintage of the NOAA hydrographic survey) go unresolved in this figure.

Pairwise ANOVA and *post-hoc* Tukey HSD tests showed that there are no statistically significant differences in vertical change with time at the 0.05 level based on geology or original water depth.

Seafloor-Elevation Change Potentials

Established metrics of vertical change were compared against vertical change potentials derived by buffer analysis using a hypothetical 10 m/y maximum rate of bed-form migration (Pendleton *et al.*, 2017). For visualization purposes, calculated vertical change metrics (based on core data) were subtracted from the potential change metrics; negative values subsequently infer measured change beyond the predicted range (based on buffer analysis), while positive values reflect measured change within the predicted range. Figure 6c depicts box plots of this data comparison by survey. While measured change values are generally within the range of established potentials (measured change < potential or calculated difference > 0), ACOE1997, ACOE2008, and ACOE2011 surveys are notable outliers. ACOE1997 cores were collected in a sparse arrangement across the entire study area, ACOE2008 cores were retrieved from attached and detached shoal fields fronting Little Assawoman Bay, and ACOE 2011 cores were collected in a tight grouping between –10 and –15 m contours seaward of Rehoboth Bay (Figure 2). The median value for the overestimation of measured change for ACOE1997 and ACOE2011 cores is close to 1 m, and most of the data distributions exceed the possible range (Figure 6c).

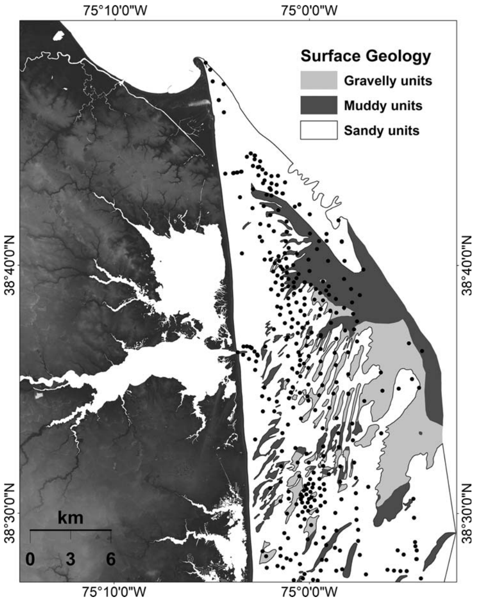


Figure 4. Surface geology map of the inner continental shelf of Delaware showing the distribution of vertical net-change metrics in context of muddy, sandy, and gravelly surface deposits. The map is simplified from Mattheus, Ramsey, and Tomlinson (in review).

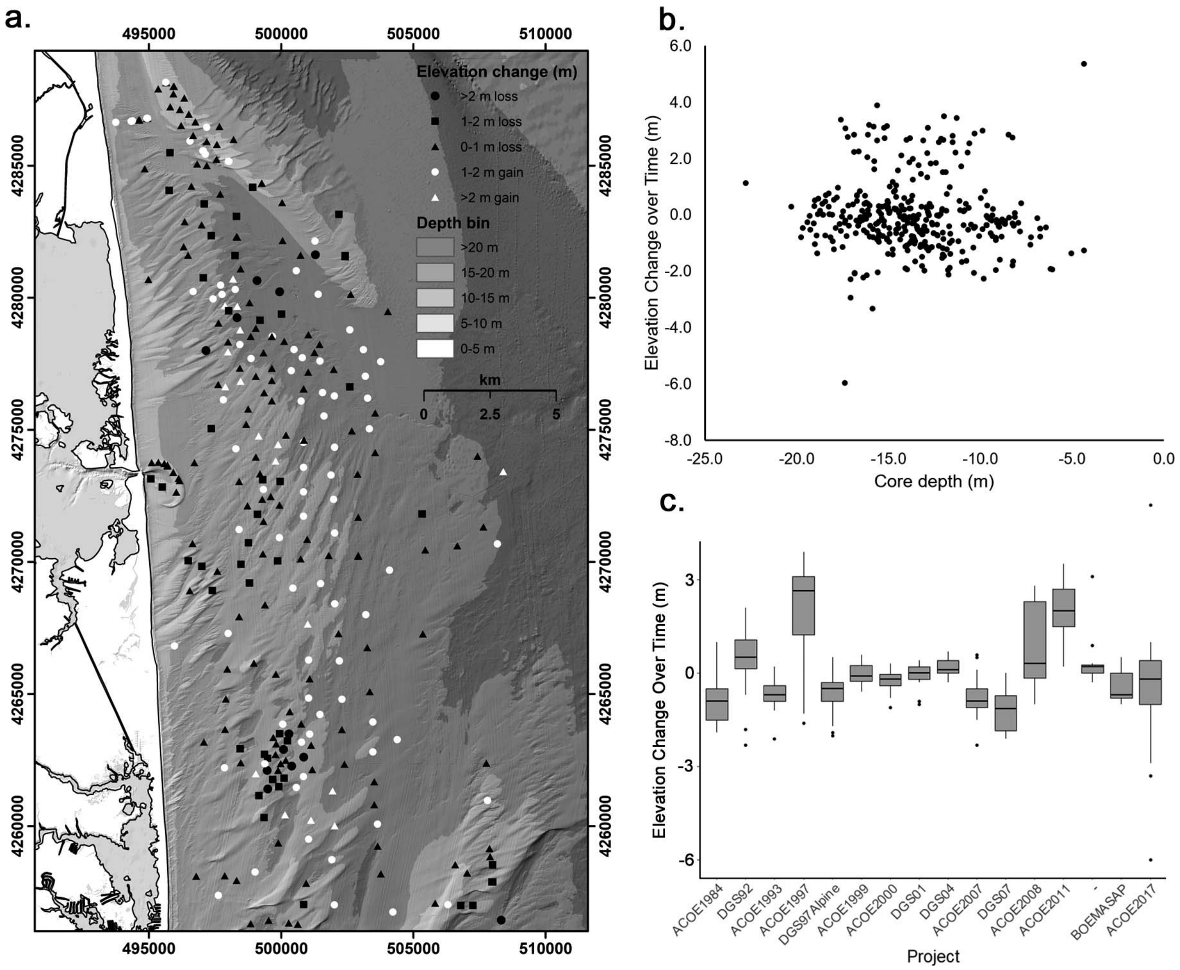


Figure 5. Multipart figure showing a map of the spatial distribution of vertical change metrics (a), corresponding graphs plotting vertical change in seafloor position against coring depth (b), and individual box-and-whisker plots of vertical change by coring project (c).

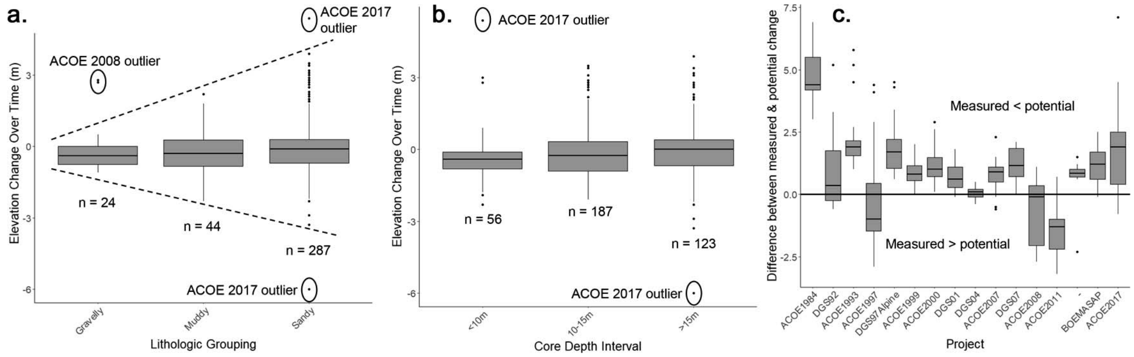


Figure 6. Box-and-whisker plots of: (a) elevation change for sandy, muddy, and gravelly units; (b) elevation change by depth bin; and (c) differences between measured change and change potentials by project.

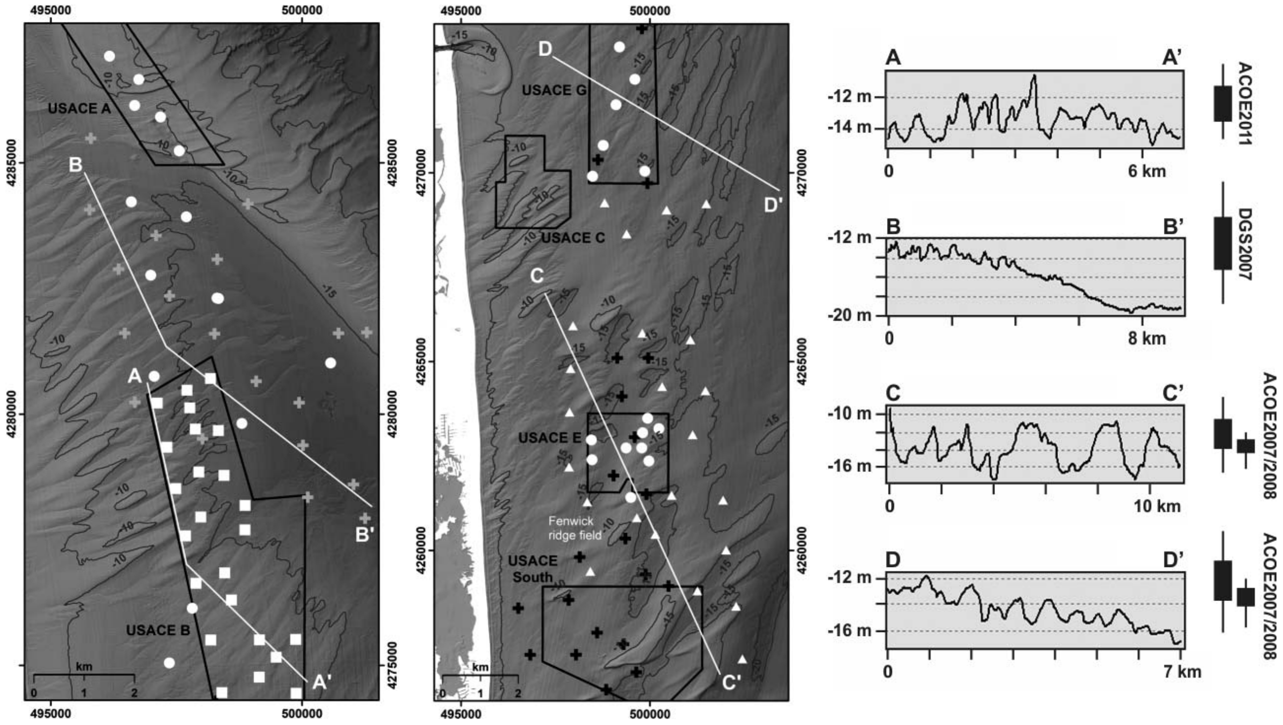


Figure 7. Illustration of seafloor topographic profiles (along with locations) across areas of ACOE1997 (black crosses), ACOE2007 (white circles), ACOE2008 (white triangles), ACOE2011 (white squares), and DGS07 (gray crosses) data coverage along with box-and-whisker plots of respective NAVD88 core elevations. Topographic profiles are based on 2007 NOAA data and are in NAVD88. Shaded relief maps, grayscale-coded by elevation, depict topographic transect and USACE lease area locations (A–G).

DISCUSSION

The following themes are discussed, before study implications are addressed: (1) patterns of vertical change inferred by the cumulative data set, taking reported depths at face value; and (2) data assumptions and uncertainties therein.

Vertical Change

Vertical changes in seafloor position were inferred from 366 core locations, the recorded depths of which were compared against a 2007 NOAA bathymetric data set. The majority of net-change metrics derived using this approach, based on a normalized vertical datum (NAVD88), fall within the expected range (based on typical bed-form relief across the area). While most inner platform shoal fields are characterized by bed-form trough-to-crest height differentials of 2 m or less (as exemplified by elevation transect D-D′), areas where shore-attached sand ridges dominate are characterized by relief of up to 4 m (see elevation transect A-A′; Figure 7). Vertical changes in seafloor position fall within the implied morphodynamic framework; only two outliers stand out, while half the data values fall between +0.3 and –0.8 m (Figure 5).

An evaluation of geospatial variables (*e.g.,* seafloor geology) against vertical change in seafloor position suggests subtle influences of surface lithology and original water depth on the seafloor position. Envelopes of vertical change are largest for sand-dominated lithotypes (*e.g.,* sheet and shoal sands) and smallest for gravelly units (*e.g.,* lag deposits; Figure 6a). If true vertical changes are captured by the core data set, they probably relate almost exclusively to the movement of sand ridges and other bed forms, which has been addressed by prior work (Pendleton *et al.*, 2017). This could help to explain the difference in net-change envelope between by lithotype. Conceptual models of late Holocene shelf evolution, based on stratigraphic insights, suggest an offshore sedimentary dynamic driven mainly by the reworking of exposed pre-Holocene units during marine transgression with little input of new clastic materials (Milliman, Pilkey, and Ross, 1972). The vertical tendency for pre-Holocene units, which are either muddy (*e.g.,* paleovalley fills) or gravelly (*e.g.,* ravinement lags), should be biased towards elevation loss (by scouring), simply given their placement within the stratigraphic framework. The observation that gravel-bearing units (*e.g.,* fluviodeltaic Beaverdam Formation; Ramsey, 1992, 1999, 2010; Ramsey and Tomlinson, 2012) appear to trend more highly towards elevation loss than sandy units supports this interpretation. Surficial sand bodies are morphologically decoupled from these underlying units, separated by a ravinement surface, but derive materials from them (due to scouring; Mattheus, 2018). Largely out of reach of modern hydrodynamic processes (given few outcrops) and characterized by a near-horizontal upper bounding surface (having been subjected to near-planar ravinement), the possibilities for positive vertical change not directly related to surficial sand bodies (*e.g.,* sheet sands) is relatively small. Positive changes recorded for muddy and gravelly surface units cored prior to 2007 are likely due to migration of sandy bed forms (postcoring). Unfortunately, there is no way of determining such a facies superposition without additional coring or grab sampling. Outcrops of the Beaverdam Formation occur largely at the transition from inner to outer platform and transition to a heavily reworked, gravelly lag deposit in the offshore direction (Figures 1 and 4; Mattheus, 2018). Low-relief sheet sand bodies are also present here, but they are thin and discontinuous. The armoring of the seafloor in these areas likely contributes to the lower elevation-change values than within major shoal fields, where greater gains and losses are attributed to bed-form migration; this dynamic appears to be reflected to some degree in the envelopes of change associated with gravelly and sandy units, respectively (Figure 6). It is important to note that pairwise ANOVA and *post-hoc* Tukey HSD tests show that there is no statistically significant difference at the 0.05 level based on geology. However, the median net-change value of –0.4 m for gravelly units is likely undervalued because many of the cores predate 2007, and some positive net-change metrics likely reflect emplacement of sheet sand. The idea of changing surface geology types with time likely also accounts for some of the change affiliated with muddy units. The sheltered, leeward portion of the HCS is where the majority of "muddy seafloor" data points are situated; muddy sands here interfinger with shoal sands and therefore have high potentials for vertical change that are unaffiliated with the muddy lithology (Figure 4). The narrowing of the change envelope from sandy to muddy to gravelly units (Figure 6a) is likely to be more pronounced than captured by this data set, given sand mobility and uncertainties concerning the contributions of facies migrations and superposition. However, the resolution of the core data set does not allow refinement of possible relationships.

While there appears to be a subtle spatial link between original water depth and subsequent vertical change (Figure 6b), the pairwise ANOVA and *post-hoc* Tukey HSD tests here also showed that there is no statistically significant difference at the 0.05 level. A covariance between water depth and lithology was observed, particularly in regards to preferential occurrence of gravelly surface units in deeper water (*i.e.* across the outer shelf platform; Figure 4). Depth-controlled facies distributions are common across continental shelves, particularly where relict sediments are being reworked (Barrie *et al.*, 1984). The degree to which this may factor into spatial trends of vertical change cannot be addressed, likely obscured by the high n values for sandy units across the full spectrum of water depths investigated (Figure 6b). There is hence likely to be a stronger control by water depth on vertical change, but it may be obscured by the complexities of bed-form dynamics, which likely fall well below the data resolution of this project. The lowest median value per depth range (–0.4 m) is associated with the foreshore/nearshore environment (in <10 m water depth), while points in the 10–15 m bin of water depth and >15 m bin in water depth are affiliated with –0.2 m and zero change, respectively. A trend toward a lower median value could relate to decreasing accommodation space in the landward direction; there is only so much accretion than can occur in the shallow nearshore region (before erosion), while deeper-water areas are more likely to preserve net-positive elevation changes. Areas above the depth of closure (around 10 m) are driven by different dynamics than those in deeper shelf waters, particularly during storm events (Kraus, Larson, and Wise, 1998; Nicholls, Birkemeier, Guan-Hong, 1998). It is therefore not out of the question that a manifestation of the different sedimentary dynamics is contained within the data set, albeit heavily obscured by noise.

While some general, margin-wide trends relating to original water depth and surface geology may find manifestation within the data set, a discussion of data resolution, potential biases, and sources of error is warranted. This not only influences interpretations of the seafloor geomorphology from core information, but it has implications for subsurface studies as well (considering that stratigraphic framework models rely on the integration of core and seismic reflection datasets).

Vertical Uncertainties

The interquartile ranges fall outside predictions for five coring projects, based on a 10 m/y maximum rate of bed-form migration (Figure 6c), which was adapted from insights into the adjacent Maryland shelf (Pendleton *et al.*, 2017). Vertical differences between the USGS DEM (anno 2007) and coring elevation (both in NAVD88 datum) for all other coring projects fall well within prediction ranges, with the exception of very few outlier points (*e.g.,* DGS2007; Figure 6c). There are several possible reasons for the observed disagreements: (1) Vertical changes are influenced significantly by processes other than the migration of surrounding bed forms and relate little to the surrounding topography. (2) Predicted ranges of vertical change are not large enough based on the hypothetical 10 m/y maximum rate of bed-form migration and time interval between data sets, implying that bed-form migration is more rapid than presently thought. (3) Vertical data inaccuracies are substantial in some cases (due to compounding vertical uncertainties).

Localized scouring and accretion due to storms and human activities are just some potential mechanisms by which vertical change could happen independently of organized/predictable bed-form migration. Dredging or sand mining, in particular, is addressed as one possible anthropogenic cause of ridge deflation and disappearance, which in turn impacts surrounding areas by helping to modify wave conditions (Hayes and Nairn, 2004). Given the data spread for individual coring projects (with kilometer-scale core spacing), localized scouring or the effects of dredging would be expected to either fall entirely below coring resolution or impact individual data points (as opposed to many or all within a given time frame). A consistent over- or underestimation of coring depths would subsequently argue against this scenario and call into question the validity of the reported coring elevations. ACOE2011 cores ($n = 22$) are distributed more or less evenly across an area under 7 km^2 in extent (USACE lease area B; Figure 7); average core density here is around 3 cores per square kilometer. This spacing is coarser than that of major bed forms of the area (250 m to 500 m). Change metrics based on in-field surveying also predate sand-mining activity within the borrow area; the same applies to other sites and project data (*e.g.,* ACOE2007 cores and lease areas G and E). The fact that nearly all net-change values within these particular coring projects exceed change potentials (Figure 6c) is strongly suggestive of an issue with vertical (core data) control, particularly considering that cores were in each case collected within a year of the NOAA bathymetric surveys. Taking the 2007 morphology of the seafloor surrounding the USACE B area into consideration (as illustrated in elevation transect A–A′; Figure 7), it is highly likely that reported core depths are systematically undervalued (*i.e*. elevations are overvalued). Core elevations for the ACOE2011 survey range from –9.9 m to –14.7 m (with the median plotting at –12.1 and the middle 50% of data points ranging from –13.6 m to –11.3 m); elevation profile A–A′ implies that only one distal end of a shore-attached (finger) shoal prominently rose above –12 m in depth. The profile location was chosen to capture the highest elevations within the survey/borrow area in 2007, which are, for the most part, the more shore-proximal reaches and should produce the least conservative measure of possible change (Figure 7). Very few cores actually lie within this high-elevation and high-relief portion of the area; most should have been collected from well below 12 m in depth (and some below 15 m). Furthermore, the high-relief and sinusoidal bed-form morphology makes it highly unlikely that all cores happened to have been retrieved from areas experiencing net accretion.

Data reporting issues are additionally suggested for the ACOE2007 and DGS07 core data sets, which were collected in the same year as the NOAA hydrographic survey (*i.e*. the USGS DEM). This comparison should have resulted in the least amount of vertical offset (given very little time for change to happen); however, a substantial offset is measured between corresponding elevation values. The combined 2007 core data set ($n = 59$), which predates the DEM data by several months, shows elevations exceeding the latter by up to 2.3 m (at an average of 1.0 m; Figure 7). Only three reported core elevation values are lower than those of the DEM, suggesting a consistent overestimation or underestimation of one or the other.

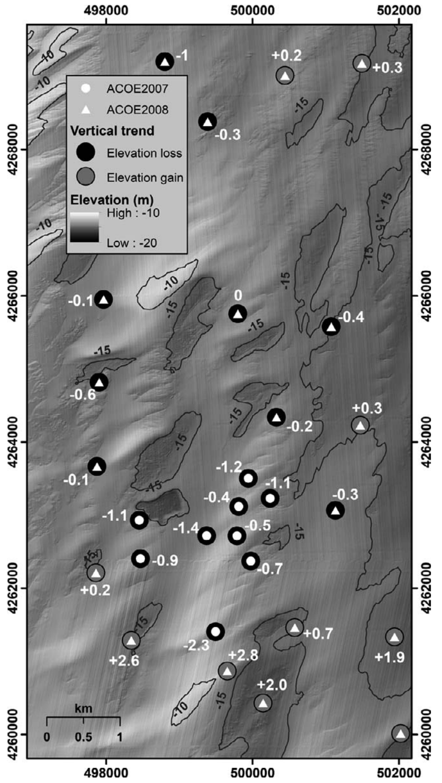
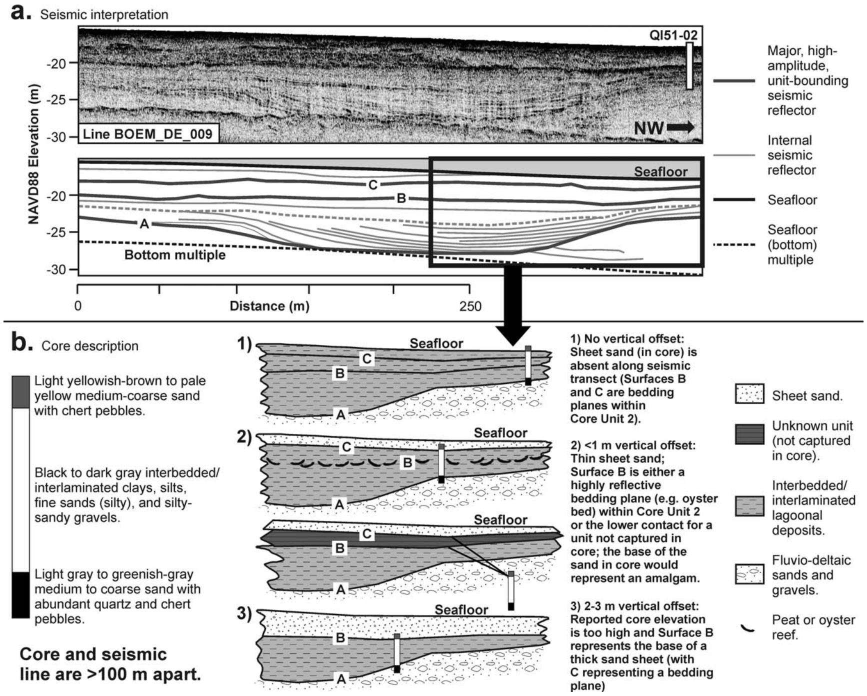


Figure 8. Grayscale-coded and contoured shaded relief map of the area surrounding USACE lease area E (outline shown in Figure 7), depicting core locations for ACOE2007 and ACOE2008 surveys, coded and labeled by calculated elevation change (positive *vs*. negative).

The observed deviations from expected net-change values call for contemplation of vertical data uncertainties. The 2007 NOAA data have a theoretical horizontal accuracy of less than 1 m (Pendleton *et al*., 2017). Hydrographic source data (ranging from 0.5 to 4 m/pixel in resolution) were interpolated using an empirical Bayesian kriging gridding algorithm (Pendleton *et al*., 2015). An assumption was made that core point locations are similarly well constrained horizontally (because surveys used differentially corrected GPS). It is unknown if a correction for antenna offset from the actual core location was accounted for, and while the horizontal positioning accuracy is at least an order of magnitude smaller than the scale of major bed forms (*i.e*. sand ridge), there is still the potential for significant translation into vertical error. A maximum bed-form slope of 26° coupled with a maximum 4 m pixel size (based on spacing of hydrographic source data) argue for a vertical uncertainty per pixel-derived elevation metric on the order of ±1 m. The vertical uncertainty due to horizontal resolution should be much less for most of the data points (given that only a few are proximal to such high slopes). The vertical uncertainty of the NOAA data set is within 0.5 m (Pendleton *et al*., 2015). While no such metric is offered in coring reports, vertical uncertainty should be comparable (*i.e*. no better) for core depths because they are similarly derived (by echo-sounding). Assuming this is likely to yield a conservative estimate of error potential, vertical uncertainty of the net-change metrics should be around ± 1 m (at best). A further assumption is that all elevation/depth data are equally based on a two-way travel time-to-depth conversion using a sound velocity of 1500 m/s in water, in adherence to established convention (Chen *et al*., 1995). This is not distinctly addressed in any of the coring reports. The combined vertical error estimate (of ±2 m) is on par with bed-form relief (Figure 1) and the range of DEM-derived and core-derived vertical change metrics (Figure 5). There is hence a high probability that, if trends exist within the data set, they are partly or wholly obscured by vertical uncertainty. An argument for the presence of some meaningful trends within “the noise” may be presented by comparing the DEM (anno 2007) to the 2008 core elevations (Figure 8). The 2008 cores plot elevations that infer a vertical change pattern consistent with 2007 topography and the probable bed-form migration pattern; in particular, cores collected near ridge lines favored erosion, while those in swales favored accretion. This is particularly noticeable in the southern part of this area, where ACOE2008 points fall below the –15 m contours (*i.e*. the trough portions of the terrain), while points to the north are situated predominantly on bathymetric highs (above –15 m) and are therefore affiliated with elevation loss (Figure 8). Only one data



1) No vertical offset: Sheet sand (in core) is absent along seismic transect (Surfaces B and C are bedding planes within Core Unit 2).

2) <1 m vertical offset: Thin sheet sand; Surface B is either a highly reflective bedding plane (e.g. oyster bed) within Core Unit 2 or the lower contact for a unit not captured in core; the base of the sand in core would represent an amalgam.

3) 2-3 m vertical offset: Reported core elevation is too high and Surface B represents the base of a thick sand sheet (with C representing a bedding plane)

Figure 9. Interpretation of a short "chirper" seismic line (from a 2015 BOEM data set) with superimposed core location (a), along with a series of conceptual models illustrating different interpretations based on realistic variances in core placement (b).

point seems to contradict this trend. Beyond this, there is little to be conclusively said regarding patterns of vertical change across the shelf and how they might relate to conceptual models of shelf dynamics, likely owing to the highly complex sedimentary dynamics that obscure patterns of organized bed-form migration.

Implications

While little can conclusively be said about shelf morphodynamics from information contained within coring reports and affiliated archival sources, the implications of this analysis are nonetheless important. First, implied differences in geomorphic response to different substrate types (*e.g.,* sandy *vs.* gravelly), while statistically insignificant, warrant additional discussion given their importance to offshore infrastructure planning and management applications. Gravel armoring of the seafloor, mapped from cores (Figure 4), and implications for sediment movement across the outer platform should factor into potential burial sites for offshore cables, for example. This relationship needs to be explored in more detail. Second, a general understanding of relative mobility of sand bodies as a function of water depth and distance from shore offers an important conceptual framework for studying sand resource areas. While coring has largely centered on state-controlled waters in the past, the progressive shift towards mapping federal waters for potential sand borrow sites (*e.g.,* the BOEM Atlantic Sand Assessment Project; Figure 2) is likely to center on areas characterized by different bed-form migration rates. Continued study of sand mobility here, from core data and geophysical mapping, should help to refine rates of change and facilitate more accurate resource assessment. Third, issues regarding vertical uncertainties, outlined and discussed in detail here, have a range of implications for stratigraphic correlation. Using core data to ground-truth seismic interpretations is particularly problematic in cases where vertical uncertainty is on the order of meters; given that "chirper" seismic data, collected at submeter vertical resolution, are commonly used for shallow stratigraphic studies, core elevation–related uncertainty may strongly impact seismic interpretation and correlation, particularly in cases where data sets were collected many years to decades apart. This is illustrated in Figure 9, which depicts a series of conceptual models for a seismic line collected in federal waters off the coast of Delaware. This type of core–seismic data integration provides the basis for stratigraphic mapping; however, an important point is made here. Three high-amplitude seismic reflections are mapped in this example (in the upper 10 m of the subsurface), relating to two major lithologic boundaries in core. Four interpretations can be made based on a 2 m vertical uncertainty in core elevation and uncertainties involving the >100 m distance between the two; these interpretations have varying implications for relating lithologic boundaries to seismic reflectors and thus have a tremendous impact on the interpretation of the thickness of the surficial sand body sampled in core. Last, an improved understanding of vertical core control benefits studies of the geologic history of coastal regions, particularly those that pertain to late Holocene development. Core-derived information, such as age dates and facies shifts, forms the cornerstone of reconstructive work. Establishing sea-level curves and inundation histories, for example, rely on tight vertical data control (Törnqvist *et al*., 2004); a better understanding of core data sets and their inaccuracies beneficial to those amassing them for paleoenvironmental work.

CONCLUSIONS

Vibracore records from offshore Delaware were studied for potential insights into decadal-scale shelf morphodynamics and better constraint of vertical data uncertainties. The data set consists of 466 sediment cores, which were collected over the past 40 years off the coast of Delaware for sand resource-assessment projects in state and federal waters. Descriptions of seafloor-sediment composition and recorded water depths were evaluated in the context of geomorphic change. While all records aided in geologic mapping of the shelf, 366 core locations offered sufficient detail of seafloor position to ensure tide correction and normalization to the NAVD88 datum. Vertical change metrics were calculated from this data subset as the difference in seafloor elevation between time of coring and a 2007 NOAA bathymetric data set. Outputs were evaluated in the context of time, shelf geology, and the morphologic compartmentalization of the seafloor. While subtle spatial trends appear to characterize the data set, these were determined to be statistically nonsignificant. Calculated metrics of vertical change fell largely within the envelope of uncertainty, derived by a compounding of spatial positioning uncertainties. Even highly detailed documentation of vertical datum and tidal correction yielded vertical accuracies within a 2 m range, at best, which approximates the relief of many of the area's shoal fields. This not only has implications for assessing shelf geomorphology from core data sets, but it should also impact seismic stratigraphic studies that rely on accurate core information for correlation purposes.

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