Grain Size and Beach Face Slope on Paraglacial Beaches of New England, USA

Authors: Jonathan D. Woodruff[1], Nicholas Venti[1], Stephen Mabee[2], Alycia DiTroia[1], Douglas Beach[1]

Affiliations:

[1]Department of Geosciences, University of Massachusetts, Amherst, MA 01003, USA

[2]Massachusetts Geological Survey, Amherst, MA 01003, USA

Corresponding author: Jonathan D. Woodruff (woodruff@umass.edu)

Keywords: Beach processes, Glacial sediments, Mixed-sand-and-gravel, Mesotidal, Microtidal, Bimodal

Highlights:

- New England is an important region with mixed sand and gravel (MSG) beaches
- Grain sizes are controlled primarily by glacial-fluvial and till sediment sources
- Beaches have bimodal grain size distributions inherited from paraglacial deposits
- Sand characteristics are the primary governor of MSG beach face slopes

Abstract:

Approximately 100 paired summer and winter transects of beach face slope and intertidal grain size were examined from 18 separate beaches in southern New England that span meso- and micro- tidal regimes. Paraglacial materials provide the principal local sediment source to beaches in this region and grain-size distribution of beaches corresponds to adjacent surficial geology. Stratified glacial fluvial deposits are the primary sediment source to sandier beaches, while till predominantly source the coarser gravel-dominated systems. When aggregated, grain size measurements exhibit a bimodal distribution of medium-to-very-coarse sand (0.25-to-1 mm) and medium-to-very-coarse gravel (10-to-64 mm), with a paucity of grains between 1-10 mm. This bimodality is also common to and likely inherited from the glacial fluvial deposits sourcing the beaches. Beach face slope is observed to increase with median grain size (D_{50}) for finer sandy systems, followed by little-to-no correlation for coarser mixed sand-and-gravel beaches where bulk D_{50} is greater than ~1 mm. This finding is consistent with previous trends observed in global beach data sets and highlights the limits of using bulk D_{50} to describe bimodal systems. When gravel is removed from the grain size distribution and the median grain size recomputed for the remaining sand fraction the familiar positive relationship between grain size and slope reemerges. Results support the growing appreciation for sand characteristics as the primary governor of intertidal slope for mixed sand and gravel systems due to its predominant control on beach face permeability and resulting transport processes.

1. Introduction

Beaches comprise approximately 31% of the world ice free shoreline (Luijendijk et al., 2018), and serve a multitude of functions including a diverse array of ecological services, key forms of flood defense, and prized locations of recreation and revenue (Martínez et al., 2007). These sedimentary systems are some of the most dynamic landforms on earth and are influenced by a variety of factors that involve waves and tides (e.g. Ivamy and Kench, 2006; Masselink and Short, 1993; Shulmeister and Kirk, 1997), sedimentary supply, sea level change and antecedent conditions (e.g. Billy et al., 2015; Carter et al., 1989; Fitzgerald and Van Heteren, 1999; Forbes et al., 1995a; Kirk, 1980; McLean and Kirk, 1969; Orford et al., 2002), and anthropogenic modifications (e.g. Hein et al., 2019; Horn and Walton, 2007).

Beach slope and grain size are defining features of beach morphology and the factors that controls these two properties have long been an area of active research. The World War II Waves Project along the Pacific Coast of North America represents an early seminal study on this topic (Bascom, 1951). Five tenets of beach morphodynamics emerged from the project: 1) that the intertidal zones of fine sandy beaches are flatter than those of coarse sandy beaches, 2) that beach material at any place is well sorted, 3) that this sorting occurs by facies, with plunge point (where wave uprush and backwash intersect) being coarsest, followed by the beach berm, the intertidal zone, dune sand, and finally the finest material found with increasing depth off-shore, 4) that beaches build seaward and steepen under gently sloping waves and are cut back and flattened by steep waves, and, 5) that wave exposure sorts material into appropriate environments along the coast. The seminal Bascom (1951) paper restricts its scope to sandy beaches, leaving the gravelly beaches for later discussion.

Subsequent research on coarser beaches indicate that they do not predictably follow the five patterns Bascom (1951) identifies in sandy systems. Regarding the slope/grain size relationship (1), flatter slopes are not always associated with finer grain sizes (McLean and Kirk, 1969) and gravelly beach faces plateau in slope before becoming steeper than sandy beaches as sand becomes excluded from the beach in coarser systems (e.g. Bujan et al., 2019). With respect to sorting (2), on some of these coarser beaches, gravel and sand are well mixed throughout while others follow a composite character with well sorted cobble and gravel in upper facies and well-sorted sand in their intertidal zones (e.g. Bluck, 1967; Jennings and Shulmeister, 2002). Thus, not only are these systems not necessarily well sorted by facies, the facies themselves follow more than one distribution, defying the ranking of faces by sort (3). Regarding wave state and cross-shore morphology described in 4, rather than predictable advance or retreat in response to a dynamic wave regime, sand and gravel beaches instead often undergo various degrees of sorting (Pontee et al., 2004). Finally, with respect to alongshore variability described in 5, instead of materials well sorted into environments along the coast according to wave energy, sediment sources and coastal barriers often bias (and in many cases predominantly control) the type and size of materials appearing on sand and gravel beaches (Fitzgerald and Van Heteren, 1999; McLean and Kirk, 1969).

Several classification systems for sand and gravel beach systems exist (e.g. Bluck, 1967; Caldwell and Williams, 1985; Carter and Orford, 1993; Jennings and Shulmeister, 2002). Carter and Orford (1993) offer a two-part classification for coarse clastic shorelines consisting of beaches as free-standing or fringing barriers. These are further subdivided into swash or driftaligned beaches. For Southern New England, USA, FitzGerald and Van Heteren (Fitzgerald and Van Heteren, 1999) define six coastline types based on several parameters including geology, antecedent topography, sediment availability, grain size and wave and tidal energy. This classification system incorporates geomorphology and indirectly includes sediment sourcing as a factor in beach characterization. Jennings and Schulmeister (2002) examine 42 gravel beach sites in New Zealand and develop a three-part classification: 1) pure gravel, 2) mixed sand and gravel (MSG) and 3) composite beaches of steeper upper-intertidal gravel and gently sloping lower-intertidal sands. Horn and Walton (2007) later suggested a 4th beach type where a steeper upper beach is composed of MSG and a lower-tide terrace of sand.

Predominant regions with detailed studies on MSG systems include the alluvial/fluvial and hinterland sourced beaches of southern New Zealand (e.g. Kirk, 1980; McLean and Kirk, 1969; Shulmeister and Kirk, 1997), as well as the paraglacial shorelines (Forbes and Syvitski, 1994) of the British Isles (Carter et al., 1987; Jennings and Smyth, 1990; Mason and Coates, 2001; Pontee et al., 2004), and eastern Canada (Carter and Orford, 1993; Forbes et al., 1995). The Northeastern coast of United States from the United States/Canadian border south through New York state represents another paraglacial coastline where MSG beaches are prevalent. Studies along this ~13,000 km stretch of coast provide detailed insight on its geomorphic evolution and response to past changes in relative sea level and sediment supply (e.g. Fitzgerald and Van Heteren, 1999; Hein et al., 2014; Kelley, 1987), yet still lacks a regional analyses on grain size and beach slope characteristics. For example, of the 2144 measurements of beach slope and grain size synthesized in a recent global compilation focused to MSG systems (Bujan et al., 2019), no data is available for the Northeastern US.

This study is focused to grain size and intertidal slope measurements from beaches of Massachusetts, which represents a particularly unique section of the Northeastern US coast in that it: 1) lies at the interface between New England's paraglacial lowlands and Mid-Atlantic Coastal Plain (Fenneman, 1938), 2) spans both micro- and meso- tidal regimes (Redfield, 1980), 3) encompasses a wide range of seasonally varying wave conditions (Woolf et al., 2002), and 4) contains a diverse array of geomorphic and grain size characteristics (Fitzgerald and Van Heteren, 1999).

2. Regional setting

The study area extends along the entire coast of Massachusetts. Prominent coastal features for this region, from north to south, include the mouth of the Merrimack River, Cape Ann, Massachusetts Bay, Cape Cod and associated islands of Martha's Vineyard and Nantucket, and Buzzards Bay (Fig. 1). During the last glaciation, the region was located near the southern extent of the ice sheet on the uplifted glacial forebulge. The continued relaxation of this forebulge has amounted to ~0.7-1.0 mm/yr of subsidence over the last few millennia (Engelhart and Horton, 2012; Peltier, 2004). However, at mean rates of 2.0 mm/yr (Portsmouth, NH) to 3.8 mm/yr (Nantucket, MA) over the past century, sea level rise in the northeastern U.S. (Zervas, 2009) eclipses gentle postglacial isostatic adjustment by nearly 2-to-5 times.

Cretaceous (and Cenozoic) sediments underlie the glacially derived and postglacial material of Cape Cod and the islands to the south in Massachusetts (Finch, 1823; Oldale and Barlow, 1986; Stone et al., 2018). This area was initially considered part of the New England Physiographic region (Fenneman, 1917, 1916), because here Cretaceous (and Cenozoic) coastal plain sediments lie largely below sea level, whereas this sequence would be extensively exposed further to the south on Long Island in New York State, if it were not covered by post-glacial materials. However, revised geographic interpretation recognizes this area as the northeastern most (exposed) extension of the Atlantic Coastal Plain as it emerges from the continental shelf (DiPietro, 2012; Fenneman, 1938; U.S. National Park Service, 2017). Provenance of sand on the eastern part of Cape Cod supports a significant reworked coastal plain component in material along the coast in this region (Ockay and Hubert, 1996).

Most of the surficial sediments in New England, including Massachusetts, were deposited during past glaciations in the late Pleistocene (Fig. 1), and largely define the sources of sediment to individual beach systems. Glacial sediments are unevenly distributed over the landscape in New England, resulting in a regional coastline that is generally sediment starved relative to other regions of the U.S. (Fitzgerald and Van Heteren, 1999). However, sediment sources can generally be categorized into three groups (Table 1): 1) stratified deposits - this includes subsets of both, 1a) coarse stratified deposits derived from glacial outwash or kame and river deltas and, 1b) fine stratified deposits originating from the erosion of fine-grained glacial marine sediments; 2) glacial till; and, 3) mixed sediments consisting of material derived from stratified deposits and glacial till in various proportions.

Tidal ranges vary depending on location. North of Cape Cod extending to the north shore of Massachusetts the tidal range is roughly 3 m (Table 1). South of Cape Cod the tidal range is approximately 1 m or less (Irish and Signell, 1992; Redfield, 1980). Based on the categorization system of Hayes (1979) study beaches north of Cape Cod are predominantly tide-dominated and beaches south of Cape Cod are classified as wave-dominated (Fitzgerald and Van Heteren, 1999). This is with the exception of the more southerly exposed beach at Rockport that is north of Cape Cod but which is a mixed tide-wave energy system (DiTroia, 2019).

Eighteen beaches were investigated in this study (Fig. 1) and fall into three main geomorphic classes according to the scheme developed by FitzGerald and Van Heteren (1999) for paraglacial barrier beach systems (Table 1; DiTroia, 2019). Salisbury and Plum Island on the north shore of Massachusetts are inlet-segmented (Type 4) beaches composed of long single barrier beaches separated by inlets with significant updrift, river, or offshore glacial fluvial sediment sources. Rockport, Nahant, Revere, Nantasket, Peggotty, Humarock, Marshfield, Barges, East and Horseneck are all headland-separated (Type 2) beaches composed of shorter, narrower barriers separated by bedrock or till headlands providing local, variably sized but less reliable sources of sediment. The remaining beaches, Plymouth, Surf, Low, Miacomet, Town and Sylvia are mainland-segmented (Type 3) beaches comprised dominantly of sand or sand with some gravel derived from glacial outwash and mixed sediment sources (till and outwash), respectively.

2.1. Sediment sources for beaches north of Cape Cod

Beginning at the northern extent of the study area, Salisbury and Plum Island beaches represent two systems sourced predominantly from relic fluvial deltaic deposits. The Boston area and north shore of Massachusetts underwent a marine incursion during initial ice retreat followed closely by isostatic rebound that produced a rapid relative sea level drop allowing the post-glacial Merrimack River to deposit a veneer of fluvial sediments and an offshore delta (Fig. 1), (Barnhardt et al., 2010; Oldale et al., 1993; Stone et al., 2006). Delta foreset beds overlying marine silts and clays are evident in offshore seismic records (Barnhardt et al., 2009). Holocene marine transgression reworked the delta and fluvial deposits providing the primary source for sediments along with riverine contributions from the adjacent Merrimack River.

The Rockport site, known locally as Long Beach, is located just south of Salisbury and Plum Island on the rocky peninsula of Cape Ann. Of all the sites, the sediment source for Rockport is one of the most difficult to assess. The beach is located in an area of numerous granite bedrock outcrops interspersed with pockets of very thin glacial till (<1-2 m) (Stone et al., 2006). The Rockport site is enclosed on each end by two bedrock headlands and comprised mostly of medium sand at low and mid tide but underlying cobbles and gravel are exposed at high tide in the winter. There is a marsh/swamp located behind the beach. During Holocene marine transgression it is likely marsh/swamp deposits were much farther seaward and the beach transgressed over the deposits as it migrated shoreward during sea level rise (Emery et al., 1967).

The Nahant site and Revere Beach are both sourced by fine-grained stratified deposits (Table 1) that underlie later post-glacial deposits throughout the Boston area (Fig. 1) (Stone et al., 2018). These fine-grained deposits are marine silts and clays deposited prior to ice retreat when relative sea level was 31 to 33 m higher than modern sea level (Stone et al., 2004b). It should be noted that Revere underwent major restoration in the 1990s and is nourished annually with up to 10 tons of fine sand to support a sandcastle building contest during the summer. Nahant also underwent a dune restoration project in 2014.

Nantasket Beach, located immediately south of Boston is adjacent to several till-based drumlins, including some eroded offshore, that served as the main source of sediment to the beach (Fig. 1).

However, it was common practice to remove the gravel armor that appeared after each winter, resulting in a lowering of the beach profile over time (FitzGerald and Rosen, 1988). This may have skewed its grain size to become somewhat finer than would otherwise be expected from a glacial till source. It is estimated that 96,000 m^3 of cobbles and gravel were removed from the beach between 1950 and 1968 by beach maintenance crews (USACE, 2012).

Along the south shore of Massachusetts Bay, Peggotty, Humarock and Marshfield beaches are mixed beaches receiving sediment from the erosion of both coarse stratified deposits (glacial outwash) and glacial till (Table 1; Fig. 1) (Stone et al., 2018). The Plymouth site is located to the south of Marshfield and lies adjacent to an extensive, glacial outwash deposit characterized by very hummocky, kame and kettle terrain (Fig. 1) (Stone et al., 2012).

2.2. Sediment sources for beaches south of Cape Cod

Miacomet and Low Beaches are located on the island of Nantucket. Similar to Plymouth, Miacomet and Low are also sourced from glacial outwash (Fig. 1), but are located approximately 4 km from the late Wisconsinan terminal moraine whereas the glacial outwash deposits near Plymouth represent a more distal and finer facies of the outwash morphosequence (Koteff and Pessl, 1981; Stone et al., 2004a).

Surf Beach, located on the south side of Cape Cod (Fig. 1), is situated just east of the contact between the Buzzards Bay recessional moraine and the “Crooked Pond deposits”. The Crooked Pond deposits are near-ice-marginal glaciofluvial fan deposits onlapping the Buzzards Bay moraine and eventually overlying the distal end of pitted outwash plains to the east (Stone and

Stone, 2019). These deposits contain cobbles and gravel and were noted as the "very coarse-grained Mashpee pitted plain deposits" recognized by Mather et al. (1942) and Masterson et al. (1997) but not previously mapped (Stone and Stone, 2019).

Town and Sylvia Beaches are located on the island of Martha's Vineyard (Fig. 1) and are comprised of sediment from a mixture of two surficial deposits, till associated with the late-Wisconsin terminal moraine and glacial outwash. The terminal moraine deposits are comprised mostly of boulders and sandy till (Stone and DiGiacomo-Cohen, 2006). Town Beach is sourced primarily from sandy till but there is a veneer of outwash overlying the till deposits (Oldale and Barlow, 1986). At Sylvia Beach, the terminal moraine is buried by thicker deposits of outwash. Accordingly, Sylvia Beach is sourced by a higher proportion of outwash than Town Beach, which contains a higher gravel/cobble component.

To the west of Martha's Vineyard lies the Elizabeth Island chain, formed from the Buzzards Bay recessional moraine. Barges Beach is located on Cuttyhunk, the southwesternmost island of the Elizabeth Islands, and is composed mostly of gravel and cobbles derived by the erosion of the recessional moraine (Fig. 1). Finally, Horseneck and East Beaches lie to the west of Buzzards Bay, along the westernmost portion of mainland Massachusetts bordering the State of Rhode Island, and are sourced by the direct erosion of glacial till in widely distributed ground moraines (Fig. 1).

3. Materials and methods

Beaches in this study were selected in collaboration with the Massachusetts Office of Coastal Zone Management in order to characterize the grain size distribution and beach slope in the intertidal zone. Between 2 and 10 intertidal transects were conducted for each of the sites depending on the length of the beach and accessibility. Transect positions were chosen at representative locations along the beach and equally spaced when possible. At each transect at least three separate samples were collected at near 1) high-tide, 2) mid-tide and 3) low-tide. When possible, additional samples were collected along storm berms and dunes but for brevity are not presented here. To assess seasonal variations in grain size distribution and slope, all transects along beaches were sampled and surveyed twice, once at the end of the summer and then revisited again at the end of the winter season. Surface sediments from the top 15-30 cm were collected from sites primarily composed of sand and pebbles (i.e. < 64 mm), and brought back to the University of Massachusetts in Amherst, MA for analysis. Exclusively sand samples were collected in 1-liter (1-quart) bags, predominantly sand samples were collected in 4-liter (1-gallon) bags and mixed sand and pebble samples in 19 -liter (5 gallon) buckets. Areas comprised primarily of cobbles and boulder (> 64 mm) were measured in the field using a gravelometer and standard pebble count techniques (Wolman, 1954).

Sediment samples were washed and dried thoroughly to remove salt and debris (sticks, seaweed, etc.). Each sample was weighed and sub-divided into fractions greater and less than 4 mm. Distributions for grains greater than 4 mm were obtained via standard sieving techniques (Udden, 1914; Wentworth, 1922)(Udden, 1914; Wentworth, 1922). Grain size distributions for sample fractions < 4 mm were measured on a CAMSIZER digital particle size analyzer capable of measuring particles between 30 μm and 4 mm (Switzer and Pile, 2015). A total of 907 grain size analyses and 86 pebble counts were conducted (See Section 7 for data availability).

Inter-tidal beach slope for each transect was obtained using a using a Real Time Kinematic (RTK) GPS survey system or a total station survey system tied to local benchmarks. Markers were placed at the head of each transect so the transects could be reoccupied the following season. A total of 235 transects were completed.

Off-shore wave conditions were independently reconstructed for each beach based on publicly available results from the United States Geological Survey (USGS) Coupled Ocean-Atmospheric-Wave-Sediment Transport (COAWST) model (Warner and others, 2010), and using the nearest deep-water grid cell to each respective beach. Modeled average wave heights directly off-shore of the sites in the 30-days preceding seasonal surveys ranged between 0.4 m and 2.5 m (bars in Fig. 2A), with storm-induced 12-hr -averaged maxima over the same intervals between 0.9 m and 7.6 m (circles in Fig. 2A). North of Cape Cod modeled wave heights were largest overall for Rockport Beach, which is south facing and located on the prominent rocky exposed headland of Cape Ann (Fig. 1). South of Cape Cod the southern facing beaches of Low and Miacomet on Nantucket were the largest. Smallest wave heights south of Cape Cod were modeled for the nearby beaches of Sylvia and Town, located on the northeast coast of Martha's Vineyard facing back to the Cape Cod mainland.

In terms of seasonality, modeled winter wave heights were consistently higher than summer at all sites (Fig. 2A), with the more exposed shorelines experiencing the greatest increases overall (e.g., an increase in 12-hr-averaged max wave heights between summer and winter of > 5 m at Rockport and 2-to-3 m for Low and Miacomet). In contrast, minimal seasonal differences in wave height occurred at more sheltered sites including the northeast facing Martha's Vineyard beaches of Sylvia and Town, where winter increases did not exceed a few cm.

4. Results

4.1 Regional and seasonal changes in grain size and beach face slope

For summer surveys a regional median grain size of 0.8 mm was observed south of Cape Cod and 0.4 mm for the north (Fig 2B). These regional medians increased in the winter surveys to 1.2 mm for the south and 0.6 mm for the north. Grain sizes were therefore greater where wave heights were higher south of Cape Cod and during the season of greater wave activity. However, these regional differences were less that the overall variance observed in grain size distributions from site to site, which ranged by an order of magnitude, and reveal the diverse types of sandy to MSG beaches evident in both tidal regions. Seasonally, grain size distributions coarsened most significantly in the winter for MSG systems (e.g. Pegotty, Humarock, Town, Surf, Barges, East and Horseneck), due in part to an apparent winnowing of sands from these locations. Sandier systems also tended to coarsen in the winter, although less significantly than at MSG locations, and with the exception of Nahant and Plymouth, where a slight winter fining was observed.

Active beach slopes of mesotidal beaches north of Cape Cod were predominantly flatter than microtidal sites to the south (Fig. 2C; slope medians of ~0.06 and ~0.12 for meso- and macro-tidal regions, respectfully). This finding is consistent with past observations of beach widths generally increasing with increasing tidal range (e.g. Masselink and Short, 1993). However, similar to grain size, intertidal slopes for individual beaches varied greatly relative to these regional medians, and did not necessarily correlate with bulk grain size. For example, beach face slopes at the meso-tidal and predominantly sandy Plum Island site were similar or steeper than a majority of slopes for coarser MSG systems at microtidal locations (e.g. Town, Surf, Barges and Horseneck). The steepest beaches observed in the study were during summer at the predominantly sandy Low Beach and during winter at the MSG East Beach. Although predominantly sandy, the steeper Plum Island and Low Beaches did exhibit some of the coarsest sand fractions of meso- and micro- tidal regions (Fig. 2B), while the lack of a gravel mode resulted in significantly lower median bulk grain sizes when compared to MSG sites. The shallowest beach face slopes in the study were observed at Nahant (Fig. 2C), which also was the finest of all beaches sampled (Fig. 2B). At individual sites most beach face slope distributions remained relatively similar seasonally, although regional medians revealed a slight drop in slope during winter at mesotidal locations and a slight winter steepening at microtidal sites (Fig. 2C). The most significant winter steepening was observed at the MSG beaches of Humarock, East and Horseneck and finer grained Miacomet, while the most significant decreases in winter slopes were at the finer grained beaches of Rockport and Low.

4.3 Grain size relative to surficial geology

Observed winter coarsening in regional medians of grain sizes indicate some oceanographic control on beach characteristics (e.g. dashed orange and blue lines in Fig. 2A and 2B). However, some of the finest-grained sandy beaches exhibited the greatest off-shore wave height, including Low and Miacomet on Nantucket, while more sheltered nearby beaches of Sylvia and Town on Martha’s Vineyard were substantially coarser (Fig. 2A and 2B). Such inconsistencies indicate that oceanographic effects are not the predominant control on grain size at the sites, supporting a basis for previous coastal classifications for this region that consider underlying geologic conditions.

Grain sizes observed on the beaches in this study generally correspond to the relative grain sizes observed within their respective source material (Fig. 3). For example, beaches associated with fine stratified deposits were the finest grained, followed by coarse stratified deposits, and then those sourced by a mixture of stratified deposits and till. Beaches sourced purely by till exhibited the greatest range of grain sizes. Rockport and Nantasket appear to be anomalous. Though till was available locally to these beaches, they are finer than expected when compared to other till-sourced beaches in the study. With respect to sorting, grain size distributions obtained from beaches either partially or fully sourced by till were poorly to very-poorly sorted (also with the exception of Rockport). In contrast, a majority of beaches sourced by stratified drift are moderately-to-well sorted (with the exception of Revere).

There is a marked distinction in grain size characteristics between beaches purely sourced by stratified drift relative to ones sourced in part or fully by coarser and more poorly sorted till. As noted, Rockport and Nantasket are presumably till-sourced but are anomalously fine-grained beaches. We suspect the reworking of barrier/marsh material during transgression at Rockport and the routine removal of gravel from Nantasket are responsible for them being anomalously fine. Peggotty Beach is also somewhat finer grained relative to other mixed-source beaches in the study. Due to public access restrictions, transects from Peggotty were limited to the finer northern section of the beach, where overwash material is returned in spring following winter storms. This sampling bias could therefore provide at least a partial explanation for the somewhat finer grains observed at the site and the lack of a predominant gravel mode evident upon visual inspection to the south. Minus these discussed exceptions, however, sediment source appears to exhibits a predominant control on grain size characteristics for beaches within the study. In contrast, grain-size distinctions based on oceanographic conditions, when separated into meso- and micro-tidal regions, or seasonal shifts in grain size due to summer-winter changes in wave climatology are more subtle (Fig. 2).

Most grain size distributions for partially or fully till sourced beaches exhibit a bimodal distribution of sand and gravel. The gravel mode for these systems result in overall coarser sediments when using common metrics such as the median or bounds of the middle quantiles (e.g. box plots in Fig. 3). However, when focused purely to the sand fraction, till sources systems were generally finer than the unimodal pure-sand beaches sourced by coarse stratified deposits (Fig. 3). Fine stratified deposits exhibited the finest sand fractions, followed by pure till sourced systems, then those sourced by a mixture of till and stratified deposits, and finally systems sourced purely from coarse stratified deposits.

Where gravel appears on the beach, we generally find it distributed throughout the exposed cross-shore facies, consistent with the “mixed” class of sand and gravel beach of Jennings and Schulmeister (2002). Synthesis of the bulk grain-size distribution of intertidal mixed sand and gravel (at least 5% > 2 mm) samples are presented in Fig. 4 (n=454) and exhibit a distinct bimodal distribution. This bimodality spans the entire study region and shows two separate peaks between medium-to-very-coarse sand (0.25 mm to 1 mm) and medium-to-very-coarse gravel (10 mm to 64 mm). These peaks are separated by a local minimum centered at approximately 1 to

10 mm. However, the overall median of the distribution occurs at 2 mm (sand/gravel transition), resulting from the coalescence of the separate sand and gravel modes. Independent analyses of just bucket and bag samples (n=368), which were mechanically sieved also show similar bimodality. Sand and gravel modes present in Fig. 4, as well as the paucity of grains between 1-10 mm, are therefore likely not an artifact of combining distributions from sieving and pebble counts, but rather a persistent feature of sand and gravel beaches of southern New England.

4.4. Beach face slope versus median grain size

In Fig. 5 data is separated further into low, mid and high tide samples to assess intertidal trends and generalizable consistencies. Comparison of median grain size and beach face slope data from this study is generally consistent with the global data set compiled by Bujan et al. (2019). Primary correspondence at all inter-tidal locations when compared to the broader Bujan et al. (2019) global composite include: 1) an increase in beach face slope with grain size for D_{50} values below 1 mm, 2) an upper limit in beach face slope of roughly 0.2, and 3) poor correlation between grain size and slope for D_{50} values that exceed ~1 mm. In general, our data also exhibit a plateau in slope beyond 1 mm that occurs within an approximate range of 0.1 and 0.2. However, a number of slope observations beyond a D_{50} of 1 mm exist well below this range in slope, particularly at mid- and high- tide locations. Categorizing grain size measurements by their degree of sorting reveals that samples with D_{50} values between 1-10 mm are all poorly sorted, likely reflecting varying contribution of grains within abutting sandy and gravel modes shown in Fig. 4. In contrast, moderately-to-well sorted samples all exhibit median grain sizes that overlap well with the previously discussed sand (0.25 mm to 1 mm) or gravel (16 mm to 64 mm) modes, and with a skew towards better sorting at high-tide locations.

Testing a common power-law fit to bulk D_{50} vs. beach face slope data results in a significant under-prediction of slope when compared to previous data available from pure gravel beaches (Fig. 6A). However, an improved fit with pure gravel systems was obtained when recomputing the median grain size on just the sand component from our mixed sand and gravel beaches (*i.e.*, removing the gravel component in the calculation, red plus signs in Fig. 6B).

5. Discussion

5.1. Origins of beach bimodality

Bimodality in grain-size distributions on southern New England beaches (Fig. 4), indicates two separate and distinct sand and gravel populations which likely have very different and divergent behaviors. Observed winter coarsening, particularly for MSG systems (Fig. 2), is primarily due to the winnowing of sand during greater wave activity that is later returned during the summer months. Anecdotal evidence for this phenomenon was observed first hand in the field with the rapid erosion of sands by storms followed by rapid deposition during surveys at the beaches of Barges, East and Humarock. In contrast, the separate gravel mode in Fig. 4 persists throughout our seasonal surveys (Fig. 2B), and is restricted to locations nearest to its till-derived source (Fig. 3). This is particularly true for headland separated beaches where gravel exchange between systems is unlikely (Fig. 1). Thus, our observations support gravel behaving more as a passive lag deposit while sand represents the more active participant (e.g. Bluck, 1967), and as such, exhibits the greater control on active beach slope (Fig. 6). However, beach bimodality is difficult to explain solely by in situ processes since this high energy environment is continually reworked by waves, which in turn provides a mechanism for sorting (Inman, 1949). A poorly sorted bimodal sand and gravel beach therefore implies a sedimentary environment in disequilibrium, as is common for most environments where sediments are derived from post-glacial deposits (e.g. Easterbrook, 1982).

Close relationships between glacial and post-glacial deposits and beach grain size described here would suggest allochthonous sourcing of beach material, consistent with many models for sand and gravel beaches generally. In Alaska (Hayes and Ruby, 1994), the British Isles (Carter and Orford, 1984), Atlantic Canada (Orford et al., 2001), and New England (Fitzgerald and Van Heteren, 1999), glacial till and post-glacial coarse stratified deposits intersect the coast. Similarly, coastal reworking of adjacent ancient coarse-grained deposits mix with sand in Taiwan (Hsieh et al., 2004), the northern Mediterranean (Ortega-Sánchez et al., 2017), and Baja California (Emery, 1955). Alternatively, fluvial inputs combined with rapidly eroding hinterlands, as in New Zealand (Bluck, 1967; Kirk, 1980) and the U.S. Pacific Coast (Bascom, 1951) can deliver both coarse and fine grained sediments directly to the beach.

McLean and Kirk (1969) provides one of the first accounts of beach bimodality based on surveys along the northeast shoreline of the South Island of New Zealand. Building on Folk and Ward (1957), sediment source was determined as the primary control on bimodal beach characteristics. Oceanographic processes (e.g. waves and tides) were evaluated as secondary controls manifested as variance around primary grain size trends. Later measurements by McLean (1970), however, revealed unimodal sediments at size fractions between bimodal gravel and sand peaks. The in-situ breakdown of parent greywacke rock derived from steep neighboring terrane was hypothesized for grain sizes in all size fractions and it was concluded that sediment source might not always be dominant in controlling beach grain size characteristics. Bimodal grain-size distributions have more recently been noted at other locations where MSG beaches are prevalent, but with differences in the size of predominant modes and no unifying resultant grain size gap (e.g. Bergillos et al., 2016; Horn and Walton, 2007; Pontee et al., 2004).

Bimodality in glacial deposits is well established (e.g. Easterbrook, 1982), where fine and coarse grained modes in basal tills results from a combination of crushing (clast size) and abrasion (matrix mode), (Dreimanis and Vagners, 1971). Transport breaks the rock down into two components – one is clast size consisting of rock fragments, the second is till matrix consisting of mineral fragments. Near the glacier source the clast size mode is always larger than matrix mode but with increasing transport distance the matrix mode grows larger relative to the clast mode (Dreimanis and Vagners, 1971). The gap between clast mode and matrix mode is thought to be the dividing line between pure crushing by glacier movement and abrasion with the threshold at 2 mm (Haldorsen, 2008). Bimodal distributions have been observed also in glacial till lag deposits located offshore of the New England Coast (Pratt and Schlee, 1969).

Bimodality is also a characteristic of river deposits (e.g. Maizels, 1993; Rădoane et al., 2008; Sambrook-Smith, 1996; Sambrook-Smith and Feruson, 1995) and by extension glacio-fluvial systems. In narrower valleys bimodal distributions can be caused by overlapping two grain size distributions of different origins. The coarse material is sourced by abrasion and hydraulic sorting whereas the source of sand material may reach the river bed through hillslope erosion. Rădoane et al. (2008) report two distinct peaks in Romania with minima in grain size between 1 and 8 mm. In other instances, high flows move coarse material while lower flows bring in sand which fills the interstices (Eynon and Walker, 1974). Mean velocities in excess of 300 cm/sec will move the gravel as bed load while sand is transported in suspension. After the gravel is deposited under lower flow conditions, the sand filters in creating strongly bimodal distributions (Eynon and Walker, 1974).

Bimodality in rivers are also commonly discussed in the form of abrupt gravel to sand transitions (e.g. Ferguson et al., 1996; Parker and Cui, 1998; Sambrook-Smith and Feruson, 1995; Shaw and Kellerhals, 1982). These gravel to sand transitions (GST) often migrate over time (Ferguson, 2003; Marr et al., 2000; Robinson and Slingerland, 1998), resulting in a depositional sequence that is as a whole distinctly bimodal (Marr et al., 2000; Paola et al., 1992). No universal theory currently exists to explain GST (Dingle et al., 2020), although the phenomena is well documented as well as a resultant 1-10 mm gap in grain size similar to that observed in Fig. 4 (e.g. Dade and Friend, 1998; Wolcott, 1988). Possible explanations for this grain size gap include grain-size dependent changes in particle breakdown or comminution (Jerolmack and Brzinski, 2010), nonlinearities in bedload transport (Ferguson, 2003), transitions from viscous-to-turbulent dependent sediment suspension thresholds (Lamb and Venditti, 2016), a switch from washload to suspended/bedload transport of sands (Dingle et al., 2020), and shifts from gravel beds to cohesive channel banks as the predominant control on channel geometries for gravel and sandy channels (Dunne and Jerolmack, 2018).

Current theory predominantly prescribes fluvial bimodality to along channel changes in river transport and is less relevant to wave-induced transport in beach settings. This is with the exception potentially of the ablation mechanisms put forth by Jerolmack and Brzinski (2010). However, unimodal beaches with distributions between 1-10 mm have been observed previously (e.g. McLean, 1970) and suggest that the bimodality observed in our New England beach systems are not globally generalizable, but rather a characteristic common to systems sourced predominantly from glacial and fluvial deposits where the presence of a 1-10 mm grain size gap is well established. Thus, we interpret the bimodality in our paraglacial beach systems to be largely inherited from the glacial and fluvial deposits upon which they are derived, yet with resulting behaviors including grain size vs. slope relationship that are unique (e.g. Fig. 6), relative to the unimodal sandy systems described in detail by Bascom er al. (1951).

5.2 Processes governing beach face slope on mixed bimodal beaches

Many have noted previously the likely impacts of bimodality on relating grain size to beach face slope (e.g. Zenkovich, 1967), first with respect to the ineffectiveness of a single metric such as median or mean grain size in describing bimodal grain size distributions (Sambrook-Smith et al., 1997), and second for the predominant roll of the sand fraction in determining beach permeability and in turn sediment transport and morphology (e.g Holmes et al., 1996; Mason et al., 1997; Mason and Coates, 2001; Quick and Dyksterhuis, 1994).

Bascom (1951) invites the use of median grain size (D_{50}) to describe beach facies because excellent sorting generally allows this single metric to adequately capture these environments. However, where sediment is not well sorted, and particularly for bimodal beaches, there is no reason to expect median or mean grain size to correspond to beach face slope. Many of the beaches described here include gravel (and cobble), yet follow the slope predicted by their sand components (Fig. 6B), while bulk median grain size cannot predict slope for these coarser bimodal systems (Fig. 6A).

All the beaches in the Massachusetts study include a substantial sand component (>25% for bulk seasonal distributions, Fig 2B), and given sand's leading role in both transport and permeability, it appears likely that the characteristic of this sand component provides a predominant control on beach slope (Fig. 6B). As at other sand and gravel beaches (Jennings and Shulmeister, 2002), there appears to be a high threshold (Masselink and Li, 2001) for coarse material content before beach face slope again begins to correspond to the bulk median grain size (Bujan et al., 2019).

Our work highlights the need for additional research on the predominant processes and potential governors of beach face slope for bimodal beaches common to the glaciated New England region. Past works provide support for two key aspects of sand preferentially controlling beach morphology in bimodal systems. First, fine grains are transported more easily, can be suspended more easily, and fall more slowly, thus potentially playing a more dynamic role in determining the morphology of bimodal mixed sand and gravel systems. Second, and likely more importantly, finer sands restrict the hydraulic conductivity of the beach, and, in turn, the degree of swash infiltration and effluent during rising and falling tides, respectively. Hydraulic conductivity increases with grain size diameter in a non-linear fashion: slowly in sand, then increasingly rapidly in gravel (Buscombe and Masselink, 2006; Horn, 2002; Krumbein and Monk, 1943). On timescales of tidal fluctuations, high porosity of gravel (D_{50} > 3mm) allows good circulation; intermediate porosity of coarse sand (3 mm > D_{50} > 0.5 mm) allows poor circulation; low porosity of medium and fine sand (D_{50} < 0.5 mm) allows virtually none (Bagnold, 1940). The amplitude and phasing of water table fluctuations at the beach face with respect to the tide are determined by the porosity, and thus the grain size of beach material should determine whether infiltration into and effusion from material shape the beach face (Masselink and Li, 2001).

As mentioned, finer sands not only restrict groundwater flow, but smaller grains are carried more easily due to their lower fall velocities, and the slope of the beach face moderates the speed of the uprush and backwash, further sorting sand. The uprush moves sand landward more effectively than the backwash because of its faster speed, shorter duration, and enhanced suspension of sediments in the boring action of breaking waves (Masselink and Hughes, 1998). Swash infiltration becomes an increasingly trivial process for medium and fine sand (<0.5 mm) (Bagnold, 1940), so fall velocity becomes the dominant factor controlling slope for finer sand beach faces (Dubois, 1972). Too coarse and the sand becomes stranded on the berm in the uprush; too fine and the sand is carried deeper offshore (Bascom, 1951). Thus, waves and tides sort sand effectively in the intertidal zone, with slope corresponding to the appropriate grain size (Bascom, 1951).

Following this explanation for beach slope, the plateau in slope near the sand-gravel transition noted by Bujan et al. (2019) could in part be caused by mixed sand and gravel systems where reduced slopes are limited by their sand component. Comparison to the mixed sand and gravel versus pure gravel beaches of Jennings and Schulmeister (2002) included in the Bujan et al. (2019) metanalysis illustrates this aspect of the aggregate data set. Specifically, the lower porosities and fall velocities of the substantial sand components on these beaches shape the shoreface resulting in shallower slopes, as observed in many of the Massachusetts beaches studied here. Considering coarser beaches generally, however, with increasing median grain size (cobble), we suspect that a diminishing sand component becomes increasingly excluded from these higher energy systems, explaining why slopes of cobbly beach faces composed predominantly of pure-gravel more reliably steepen beyond mixed sand and gravel systems with median grain size in the gravel range (e.g. Fig. 6B; Jennings and Schulmeister, 2002).

5.3 Oceanographic Impacts

Oceanographic factors may provide additional secondary explanations for the scatter observed between grain size and slope along the Massachusetts beaches, particularly when gravel is removed and comparisons are made between median sand size and beach face slope. Increasing tidal range typically corresponds to an increase in beach width (Masselink and Short, 1993), and could in part explain the shallower slopes for the meso-tidal beaches relative to their micro-tidal counterparts (Fig. 2C). However, the same general sand D_{50} vs. slope relationships hold even when observations are categorized into their predominant oceanographic setting (Fig. 7). This is true both in terms of micro- vs. meso-tidal ranges (Fig. 7, top right panel) and summer-winter wave climatology (Fig. 7, bottom right). If true, the general decrease in bulk grain size observed for our meso-tidal relative to micro-tidal systems would provide support for feedbacks, where beach slope is adjusted in part via a reduction in grain size for these systems.

We suspect tidal regime to be the predominant control on regional differences in slope north and south of Cape Cod. However, an alternative explanation for greater slopes for beaches south of Cape Cod is that there is a paucity of finer-grained beaches in this region as a result of its unique depositional setting. Whereas in the north fine-grained glaciomarine deposits are widespread across Massachusetts Bay and Cape Cod Bay, many of the beaches south of Cape Cod are proximal to the late Wisconsinan terminal moraine or the Buzzards Bay recessional moraine. Accordingly, this close proximity to the ice margin may have resulted in higher depositional energy producing a general coarsening of sand within associated stratified deposits. The southern mixed till/stratified source beaches of Sylvia, Town and Surf show some evidence of courser sands when compared to the northern beaches of Peggotty, Humarock and Marshfield (Fig. 3). However north-south differences for other sediment sourcing categories in Fig. 3 are less conclusive.

With respect to oceanographic conditions, waves provide another potential control on beach characteristics in addition to tides (e.g. Masselink and Short, 1993). Primary evidence for waves controlling grain size at our sites include a general coarsening in median grain size for the winter surveys relative to summer (blue vs. orange dashed lines in Fig. 2B). When categorized by season, winter beach face slopes appears to plot slightly lower than its summer counterpart at the northern meso-tidal locations (Fig. 2C), consistent with flattening of the beach during landward translation of the face during winter. Although we observed clear landward retreat of some of the sandier beaches (Salisbury, Peggotty, Rockport, Low) during winter, on coarser beaches advance/retreat results are mixed from one transect to the next and the beach appeared to move little in aggregate seasonally. We therefore interpret the general summer-to-winter bulk coarsening in Fig. 2 as representing a partial removal of some of the sand fraction in the surface layer of these beaches. An increase in winter wave activity therefore appears sufficient enough to winnow sands and coarsen the resultant median grain size (Fig. 2B), but the amounts removed are insufficient to cause a significant, generalizable seasonal change in beach face slope (Fig. 2C).

5.4 Future Work

Considering sand versus MSG beaches, we return to Bascom's five tenets with greater appreciation for how coarse material interrupts patterns predicted for otherwise sandy systems. Regarding 1) that the intertidal zones of fine sandy beaches are flatter than those of coarse sandy beaches, we find that this holds true for the sand fraction. Future work might build on how sand continues to control beach slope when gravel is included. Regarding 2) that beach material at any place is well sorted, we find this true for the sand fraction, though not true for bulk material. Previous studies recognize both mixed (*e.g.* this study) and composite classes of sand and gravel beaches, where good sorting at any point is followed. Why one form or the other appears along the coast is an open question in beach research. To 3) that sorting occurs by facies, with plunge point (where wave uprush and backwash intersect) being coarsest, then summer berm, the intertidal zone, dune sand, and the finest material with increasing depth under water, we find a slightly different pattern with the coarsest material found stranded within high-tide facies. Instead of clear evidence for 4) that beaches build seaward and steepen under gently sloping waves and are cut back and flattened by steep waves, we find that high-energy waves winnow sand to leave a coarser winter beach face, whereas sand becomes reincorporated under low energy summer waves. MSG beaches use a step to accommodate wave energy (e.g. Masselink et al., 2010), which may explain insensitivity in breach face slope and facies positions to changing wave climate observed here. Finally, we cannot resolve 5) that wave exposure sorts material into appropriate environments along the coast. Along the complex postglacial coast the general distribution of the sand component's distribution on the beach is poorly understood. Further research is needed to evaluate how availability of nearby sand deposits determines fine beach material versus in situ sorting of this sand fraction into appropriate coastal environments by oceanographic processes.

6. Conclusions

Post-glaciated beaches in the New England region are relatively unique to the U.S., yet represent important examples of the global subset of beaches composed of both sand and gravel. Glacial till and outwash/fluvial deposits are the primary sources of gravel and sand to local beaches in the region, respectively, and the relative contribution of these two sources serve as the predominant control on aggregate beach grain size. Oceanographic factors exhibit secondary controls with an increase in beach slope for micro- versus meso-tidal systems, and a general summer-to-winter coarsening due to the seasonal winnowing of sands. Combining all beach grain size distributions from the region reveals two separate modes of medium-to-very-coarse sand and medium-to-very-coarse gravel separated by a lack of grains between 1 and 10 mm. This gap in grain size is common to paraglacial and fluvial deposits upon which sediment to regional beaches in New England are derived and suggests an allochthonous rather than autochthonous cause. Median grain size or D_{50} is a common metric used for predicting active beach slope for unimodal beaches, but our work supports past observations on D_{50} being less effective when applied to bimodal mixed sand and gravel beaches. Similar to these past studies we observe beach slope predictably increases with grain size up to a bulk D_{50} of ~1 mm, and a lack of correspondence beyond this median size. For coarser mixed sand and gravel systems the D_{50} of the sand fraction better predicts beach face slope, and follows a similar D_{50} vs. slope relationship as that observed using bulk D_{50} for finer, sandy unimodal beaches. Comparisons to pure gravel beaches reveals that a relatively high fractional content of gravel is likely required in order for beach face slope to correspond to bulk median grain size. Grain size distributions of sand serve as the primary governor of beach face permeability and sediment transport in bimodal systems, which together likely explain why it has greater observed control on beach morphology for mixed sand and gravel systems.

Acknowledgements

University of Massachusetts undergraduates J. Light, M. Cashman, S. Gessay, S. Osgood, N. Doiron, A. Chica, J. Healey, J. Jurnack, M. Koerth, and P. Southard assisted in the field and lab work. M. Mansfield, R. Haney, J. Burtner, K. Glenn, and J. Knisel from MA Coastal Zone Management gave guidance and logistical support throughout the project. M. Borrelli from UMass-Boston and Center for Coastal Studies and R. Newton of Smith College contributed technical assistance and positioning equipment for beach surveys, and J. Warner assisted with access to COAWST model results. Woodruff is grateful for support by the University of Maine Darling Marine Center which provided residency during the completion of this manuscript. This research was funded by the U.S. Department of Interior, Bureau of Ocean Energy Management under cooperative agreement M14AC00006. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Government. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Government.

Figure Captions

Figure 1. Regional Massachusetts coastline (upper left panel) and study area locations shown in panels A-F, along with transect locations (black circles), surficial geology with key provided. Text boxes indicate location of each beach in study as well as its predominant surficial geology (modified from Stone and others, 2018).

Figure 2: (A) Significant wave height - H_{sig}, and (B) combined grain size and (C) beach face slope distributions for summer (orange) and winter (blue) surveys. Beach sites arranged north-to-south (left-to-right). H_{sig} averages (bars) and 12-hr averaged maxima (circles) are over the 30-days prior to surveying. Box plots in B and C include the median (thick horizonal line), bounds average 12-hr maxima and median grain size and slope for meso- and micro- tidal regions shown as dashed horizonal orange and blue lines, respectfully.

Figure 3: Bulk grain size distribution for sites and arranged with respect to their predominant sediment source. Box plots include the median (thick horizonal line), bounds of middle quantiles (boxes) and 10th-to-90th percentiles (thin vertical line).

Figure 4: Composite grain size distribution of binned (blue) and cumulative (red) percent for all intertidal mixed sand and gravel samples (MSG). Here MSG samples are defined as greater than 5% of distribution exceeding 2 mm (n=454).

Figure 5: Median (D_{50}) grain size versus beach face slope for low tide (left panel), mid tide (middle panel) and high tide (right panel) compared to the global data set of Bujan et al. (2019). Moderately-to-well sorted samples (circles) and poorly sorted samples (plus markers) are defined

by criteria presented by Blott and Pye (2001) . The same global data set from Bujan et al. (2019) is shown in each panel (gray asterisk) where grain sizes represents either a D_{50} or mean and were obtained by a variety of methods provided by references therein.

Figure 6: (A) Median grain size versus beach face slope for MSG (plus signs) and pure sand beaches (black circles) in this study compared to data by Jennings and Schulmeister (2002) for pure gravel beaches (J&S,2002, black triangles). Left panel is bulk D_{50} grain size and right panel is the median grain size of just the isolated sand fraction (i.e. median for distribution < 2 mm). Power law fits (dashed lines) are provided for bulk D_{50} and median size in sand fraction (Ds_{50}) versus beach face slope (S). Values of best fit for right panel in the form of $S=a*Ds_{50}$^b+c and fitted parameters of a = -0.10, b = -0.37, and c = 0.22.

Figure 7: Beach face slope versus bulk median grain size (left panels) and median grain size for sand fraction (right panels) categorized by tidal region (top panels) and season (bottom panels).

References

Bagnold, R.A., 1940. Beach formation by waves: some model experiments in a wave tank. Journal of the Institution of Civil Engineers 15, 27–52.

Barnhardt, W.A., Ackerman, S.D., Andrews, B.D., Baldwin, W.E., 2010. Geophysical and sampling data from the inner continental shelf: Duxbury to Hull, Massachusetts. US Geological Survey.

Barnhardt, W.A., Andrews, B.D., Ackerman, S.D., Baldwin, W.E., Hein, C.J., 2009. High-Resolution Geologic Mapping of the Inner Continental Shelf: Cape Ann to Salisbury Beach, Massachusetts. US Geological Survey.

Bascom, W.N., 1951. The relationship between sand size and beach-face slope. Eos, Transactions American Geophysical Union 32, 866–874. https://doi.org/10.1029/TR032i006p00866

Bergillos, R.J., Ortega-Sánchez, M., Masselink, G., Losada, M.A., 2016. Morpho-sedimentary dynamics of a micro-tidal mixed sand and gravel beach, Playa Granada, southern Spain. Marine Geology 379, 28–38. https://doi.org/10.1016/j.margeo.2016.05.003

Billy, J., Robin, N., Hein, C.J., Certain, R., FitzGerald, D.M., 2015. Insight into the late Holocene sea-level changes in the NW Atlantic from a paraglacial beach-ridge plain south of Newfoundland. Geomorphology 248, 134–146. https://doi.org/10.1016/j.geomorph.2015.07.033

Blott, S.J., Pye, K., 2001. GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surface Processes and Landforms 26, 1237–1248. https://doi.org/10.1002/esp.261

Bluck, B.J., 1967. Sedimentation of beach gravels; examples from South Wales. Journal of Sedimentary Research 37, 128–156.

Bujan, N., Cox, R., Masselink, G., 2019. From fine sand to boulders: Examining the relationship between beach-face slope and sediment size. Marine Geology 417, 106012. https://doi.org/10.1016/j.margeo.2019.106012

Buscombe, D., Masselink, G., 2006. Concepts in gravel beach dynamics. Earth-Science Reviews 79, 33–52. https://doi.org/10.1016/j.earscirev.2006.06.003

Caldwell, N.E., Williams, A.T., 1985. The Role of Beach Profile Configuration in the Discrimination between Differing Depositional Environments Affecting Coarse Clastic Beaches. Journal of Coastal Research 1, 129–139.

Carter, R.W.G., Forbes, D.L., Jennings, S.C., Orford, J.D., Shaw, J., Taylor, R.B., 1989. Barrier and lagoon coast evolution under differing relative sea-level regimes: examples from Ireland and Nova Scotia. Marine Geology 88, 221–242. https://doi.org/10.1016/0025-3227(89)90099-6

Carter, R.W.G., Johnston, T.W., McKenna, J., Orford, J.D., 1987. Sea-level, sediment supply and coastal changes: examples from the coast of Ireland. Progress in Oceanography 18, 79–101.

Carter, R.W.G., Orford, J.D., 1993. The Morphodynamics of Coarse Clastic Beaches and Barriers: A Short- and Long-term Perspective. Journal of Coastal Research 158–179.

Carter, R.W.G., Orford, J.D., 1984. Coarse clastic barrier beaches: a discussion of the distinctive dynamic and morphosedimentary characteristics, in: Developments in Sedimentology. Elsevier, pp. 377–389.

Dade, W.B., Friend, P.F., 1998. Grain-Size, Sediment-Transport Regime, and Channel Slope in Alluvial Rivers. The Journal of Geology 106, 661–676. https://doi.org/10.1086/516052

Dingle, E.H., Sinclair, H.D., Venditti, J.G., Attal, M., Kinnaird, T.C., Creed, M., Quick, L., Nittrouer, J.A., Gautam, D., 2020. Sediment dynamics across gravel-sand transitions: Implications for river stability and floodplain recycling. Geology 48, 468–472. https://doi.org/10.1130/G46909.1

DiPietro, J.A., 2012. Landscape evolution in the United States: an introduction to the geography, geology, and natural history. Elsevier.

DiTroia, A., 2019. Legacy Sediment Controls on Post-Glacial Beaches of Massachusetts (Masters Theses). University of Massachusetts, Amherst, MA USA.

Dreimanis, A., Vagners, U.J., 1971. Bimodal distribution of rock and mineral fragments in basal tills, in: Goldthwait, R.P. (Ed.), Till, a Symposium. Ohio State University Press, Columbus, Ohio, pp. 237–250.

Dubois, R.N., 1972. Inverse relation between foreshore slope and mean grain size as a function of the heavy mineral content. Geological Society of America Bulletin 83, 871–876.

Dunne, K.B.J., Jerolmack, D.J., 2018. Evidence of, and a proposed explanation for, bimodal transport states in alluvial rivers. Earth Surf. Dynam. 6, 583–594. https://doi.org/10.5194/esurf-6-583-2018

Easterbrook, D.J., 1982. Characteristic features of glacial sediments, in: Sandstone Depositional Environments. American Association of Petroleum Geologists.

Emery, K.O., 1955. Grain Size of Marine Beach Gravels. The Journal of Geology 63, 39–49.

Emery, K.O., Wigley, R.L., Bartlett, A.S., Rubin, M., Barghoorn, E.S., 1967. Freshwater peat on the continental shelf. Science 158, 1301–1307. https://doi.org/10.1126/science.158.3806.1301

Engelhart, S.E., Horton, B.P., 2012. Holocene sea level database for the Atlantic coast of the United States. Quaternary Science Reviews 54, 12–25.

Eynon, G., Walker, R.G., 1974. Facies relationships in Pleistocene outwash gravels, southern Ontario: a model for bar growth in braided rivers. Sedimentology 21, 43–70.

Fenneman, N.M., 1938. Physiography of Eastern United States.

Fenneman, N.M., 1917. Physiographic divisions of the United States. Proc. Natl. Acad. Sci. 3, 17–22.

Fenneman, N.M., 1916. Physiographic divisions of the United States. Ann. Assoc. Amer. Geog. 6, 19–98.

Ferguson, R., Hoey, T., Wathen, S., Werritty, A., 1996. Field evidence for rapid downstream fining of river gravels through selective transport. Geology 24, 179–182.

Ferguson, R.I., 2003. Emergence of abrupt gravel to sand transitions along rivers through sorting processes. Geology 31, 159–162.

Finch, J., 1823. Geological Essay on the Tertiary Formations in America...

FitzGerald, D.M., Rosen, P.S., 1988. USA--Massachusetts, in: Walker, H.J. (Ed.), Artificial Structures and Shorelines, The GeoJournal Library. Springer, pp. 545–560.

Fitzgerald, D.M., Van Heteren, S., 1999. Classification of paraglacial barrier systems: coastal New England, USA. Sedimentology 46, 1083–1108. https://doi.org/10.1046/j.1365-3091.1999.00266.x

Folk, R.L., Ward, W.C., 1957. Brazos River Bar: A Study in the Significance of Grain Size Parameters. Journal of Sedimentary Petrology 27, 3–26.

Forbes, D.L., Orford, J.D., Carter, R.W.G., Shaw, J., Jennings, S.C., 1995. Morphodynamic evolution, self-organisation, and instability of coarse-clastic barriers on paraglacial coasts. Marine Geology 126, 63–85. https://doi.org/10.1016/0025-3227(95)00066-8

Forbes, D.L., Syvitski, J.P., 1994. Paraglacial coasts. Coastal Evolution: Late Quaternary Shoreline Morphodynamics. Cambridge University Press, Cambridge 373–424.

Haldorsen, S., 2008. Grain-size distribution of subglacial till and its realtion to glacial scrushing and abrasion. Boreas 10, 91–105. https://doi.org/10.1111/j.1502-3885.1981.tb00472.x

Hayes, M.O., 1979. Barrier island morphology as a function of tidal and wave regime. In: Leatherman SP (ed) Barrier Islands. Academic Press, New York 1, 27.

Hayes, M.O., Ruby, C.H., 1994. Barriers of Pacific Alaska, in: Geology of Holocene Barrier Island Systems. Springer, Berlin, Heidelberg, pp. 395–433.

Hein, C.J., Fallon, A.R., Rosen, P., Hoagland, P., Georgiou, I.Y., FitzGerald, D.M., Morris, M., Baker, S., Marino, G.B., Fitzsimons, G., 2019. Shoreline Dynamics Along a Developed River Mouth Barrier Island: Multi-Decadal Cycles of Erosion and Event-Driven Mitigation. Front. Earth Sci. 7, 103. https://doi.org/10.3389/feart.2019.00103

Hein, C.J., FitzGerald, D.M., Buynevich, I.V., Van Heteren, S., Kelley, J.T., 2014. Evolution of paraglacial coasts in response to changes in fluvial sediment supply. Geological Society, London, Special Publications 388, 247–280.

Holmes, P., Baldock, T.E., Chan, R.T., Neshaei, M.A.L., 1996. Beach evolution under random waves. Presented at the 25th International Conference on Coastal Engineering, pp. 3006–3019.

Horn, D.P., 2002. Beach groundwater dynamics. Geomorphology 48, 121–146. https://doi.org/10.1016/S0169-555X(02)00178-2

Horn, D.P., Walton, S.M., 2007. Spatial and temporal variations of sediment size on a mixed sand and gravel beach. Sedimentary Geology 202, 509–528. https://doi.org/10.1016/j.sedgeo.2007.03.023

Hsieh, M.-L., Liew, P.-M., Hsu, M.-Y., 2004. Holocene tectonic uplift on the Hua-tung coast, eastern Taiwan. Quaternary International 115–116, 47–70. https://doi.org/10.1016/S1040-6182(03)00096-X

Inman, D.L., 1949. Sorting of sediments in the light of fluid mechanics. Journal of Sedimentary Research 19, 51–70.

Irish, J.D., Signell, R.P., 1992. Tides of Massachusetts and Cape Cod Bays. Woods Hole Oceanographic Institution.

Ivamy, M.C., Kench, P.S., 2006. Hydrodynamics and morphological adjustment of a mixed sand and gravel beach, Torere, Bay of Plenty, New Zealand. Marine Geology 228, 137–152. https://doi.org/10.1016/j.margeo.2006.01.002

Jennings, R., Shulmeister, J., 2002. A field based classification scheme for gravel beaches. Marine Geology 186, 211–228.

Jennings, S., Smyth, C., 1990. Holocene evolution of the gravel coastline of East Sussex. Proceedings of the Geologists' Association 101, 213–224.

Jerolmack, D.J., Brzinski, T.A., 2010. Equivalence of abrupt grain-size transitions in alluvial rivers and eolian sand seas: A hypothesis. Geology 38, 719–722. https://doi.org/10.1130/G30922.1

Kelley, J.T., 1987. An Inventory of Coastal Environments and Classification of Maine's Glaciated Shoreline, in: FitzGerald, D.M., Rosen, P.S. (Eds.), Glaciated Coasts. Academic Press, Inc, San Diego, pp. 151–176.

Kirk, R.M., 1980. Mixed sand and gravel beaches: morphology, processes and sediments. Progress in Physical Geography 4, 189–210.

Koteff, C., Pessl, F., 1981. Systematic ice retreat in New England (U.S. Geological Survey Professional Paper No. 1179).

Krumbein, W.C., Monk, G.D., 1943. Permeability as a function of the size parameters of unconsolidated sand. Transactions of the AIME 151, 153–163.

Lamb, M.P., Venditti, J.G., 2016. The grain size gap and abrupt gravel-sand transitions in rivers due to suspension fallout. Geophysical Research Letters 43, 3777–3785. https://doi.org/10.1002/2016GL068713

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., Aarninkhof, S., 2018. The State of the World's Beaches. Sci Rep 8, 6641. https://doi.org/10.1038/s41598-018-24630-6

Maizels, J., 1993. Lithofacies variations within sandur deposits: the role of runoff regime, flow dynamics and sediment supply characteristics. Sedimentary Geology 85, 299–325. https://doi.org/10.1016/0037-0738(93)90090-R

Marr, J.G., Swenson, J.B., Paola, C., Voller, V.R., 2000. A two-diffusion model of fluvial stratigraphy in closed depositional basins. Basin Research 12, 381–398. https://doi.org/10.1111/j.1365-2117.2000.00134.x

Martínez, M.L., Intralawan, A., Vázquez, G., Pérez-Maqueo, O., Sutton, P., Landgrave, R., 2007. The coasts of our world: Ecological, economic and social importance. Ecological Economics 63, 254–272. https://doi.org/10.1016/j.ecolecon.2006.10.022

Mason, T., Coates, T.T., 2001. Sediment Transport Processes on Mixed Beaches: A Review for Shoreline Management. Journal of Coastal Research 17, 645–657.

Mason, T., Voulgaris, G., Simmonds, D.J., Collins, M.B., 1997. Hydrodynamics and sediment transport on composite (mixed sand/shingle) and sand beaches: A comparison, in: Thornton, E.B. (Ed.), Coastal Dynamics. American Society of Civil Engineers, New York, pp. 48–57.

Masselink, G., Hughes, M., 1998. Field investigation of sediment transport in the swash zone. Continental Shelf Research 18, 1179–1199. https://doi.org/10.1016/S0278-4343(98)00027-2

Masselink, G., Li, L., 2001. The role of swash infiltration in determining the beachface gradient: a numerical study. Marine Geology 176, 139–156.

Masselink, G., Russell, P., Blenkinsopp, C., Turner, I., 2010. Swash zone sediment transport, step dynamics and morphological response on a gravel beach. Marine Geology 274, 50–68. https://doi.org/10.1016/j.margeo.2010.03.005

Masselink, G., Short, A.D., 1993. The Effect of Tide Range on Beach Morphodynamics and Morphology: A Conceptual Beach Model. Journal of Coastal Research 9, 785–800.

Masterson, J.P., Stone, B.D., Walter, D.A., Savoie, J.G., 1997. Hydrogeologic framework of western Cape Cod, Massachusetts (U.S. Geological Survey Hydrologic Investigations Atlas No. 741).

Mather, K.F., Goldthwait, R.P., Thiesmeyer, L.R., 1942. Pleistocene geology of western Cape Cod, Massachusetts. Bulletin of the Geological Society of America 53, 1127–1174.

McLean, R.F., 1970. Variations in grain-size and sorting on two kaikoura beaches. New Zealand Journal of Marine and Freshwater Research 4, 141–164. https://doi.org/10.1080/00288330.1970.9515334

McLean, R.F., Kirk, R.M., 1969. Relationships between grain size, size-sorting, and foreshore slope on mixed sand - shingle beaches. New Zealand Journal of Geology and Geophysics 12, 138–155. https://doi.org/10.1080/00288306.1969.10420231

Ockay, C., Hubert, J.F., 1996. Mineralogy and provenance of Pleistocene outwash-plain and modern beach sands of outer Cape Cod, Massachusetts, USA. Marine Geology 130, 121–137. https://doi.org/10.1016/0025-3227(95)00125-5

Oldale, R.N., Barlow, R.A., 1986. Geologic map of Cape Cod and the islands, Massachusetts (Miscellaneous Investigations Series Map No. I–1763). United States Geological Survey.

Oldale, R.N., Colman, S.M., Jones, G.A., 1993. Radiocarbon ages from two submerged strandline features in the western Gulf of Maine and a sea-level curve for the northeastern Massachusetts coastal region. Quaternary Research 40, 38–45.

Orford, J.D., Forbes, D.L., Jennings, S.C., 2002. Organisational controls, typologies and time scales of paraglacial gravel-dominated coastal systems. Geomorphology 48, 51–85. https://doi.org/10.1016/S0169-555X(02)00175-7

Orford, J.D., Jennings, S.C., Forbes, D.L., 2001. Origin, development, reworking and breakdown of gravel-dominated coastal barriers in Atlantic Canada: future scenarios for the British coast, in: Packham, J.R., Barnes, R.S.K., Neals, A. (Eds.), Ecology & Geomorphology of Coastal Shingle. Westbury, pp. 23–55.

Ortega-Sánchez, M., Bergillos, R.J., López-Ruiz, A., Losada, M.A., 2017. Morphodynamics of mediterranean mixed sand and gravel coasts. Springer.

Paola, C., Heller, P.L., Angevine, C.L., 1992. The large-scale dynamics of grain-size variation in alluvial basins, 1: Theory. Basin research 4, 73–90.

Parker, G., Cui, Y., 1998. The arrested gravel front: stable gravel-sand transitions in rivers Part 1: Simplified analytical solution. Journal of hydraulic research 36, 75–100.

Peltier, W.R., 2004. Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2) model and GRACE. Annu. Rev. Earth Planet. Sci. 32, 111–149.

Pontee, N.I., Pye, K., Blott, S.J., 2004. Morphodynamic Behaviour and Sedimentary Variation of Mixed Sand and Gravel Beaches, Suffolk, UK. Journal of Coastal Research 20, 256–276.

Pratt, R.M., Schlee, J., 1969. Glaciation on the Continental Margin off New England. Geol Soc America Bull 80, 2335–2342. https://doi.org/10.1130/0016-7606(1969)80[2335:GOTCMO]2.0.CO;2

Quick, M.C., Dyksterhuis, P., 1994. Cross-shore transport for beaches of mixed sand and gravel, in: International Symposium: Waves—Physical and Numerical Modeling. Canadian Society of Civil Engineers. pp. 1443–1452.

Rădoane, M., Rădoane, N., Dumitriu, D., Miclăuş, C., 2008. Downstream variation in bed sediment size along the East Carpathian rivers: evidence of the role of sediment sources. Earth Surface Processes and Landforms 33, 674–694. https://doi.org/10.1002/esp.1568

Redfield, A.C., 1980. The tides of the waters of New England and New York. Woods Hole Oceanographic Institution.

Robinson, R.A.J., Slingerland, R.L., 1998. Origin of fluvial grain-size trends in a foreland basin; the Pocono Formation on the central Appalachian Basin. Journal of Sedimentary Research 68, 473–486. https://doi.org/10.2110/jsr.68.473

Sambrook-Smith, G.H., 1996. Bimodal fluvial bed sediments: origin, spatial extent and processes. Progress in Physical Geography 20, 402–417.

Sambrook-Smith, G.H., Feruson, R.I., 1995. The Gravel-Sand Transition Along River Channels. SEPM JSR A65, 423–430. https://doi.org/10.1306/D42680E0-2B26-11D7-8648000102C1865D

Sambrook-Smith, G.H., Nicholas, A.P., Ferguson, R.I., 1997. Measuring and defining bimodal sediments: Problems and implications. Water Resources Research 33, 1179–1185. https://doi.org/10.1029/97WR00365

Shaw, J., Kellerhals, R., 1982. The composition of recent alluvial gravels in Alberta river beds, Bull. 41, 151 pp. Alberta Research Council Bulletin 41, 151.

Shulmeister, J., Kirk, R.M., 1997. Holocene fluvial-coastal interactions on a mixed sand and sand and gravel beach system, North Canterbury, New Zealand. Catena 30, 337–355.

Stone, B.D., DiGiacomo-Cohen, M.L., 2006. Surficial geologic map of the Pocasset-Provincetown-Cuttyhunk-Nantucket 24-quadrangle area of Cape Cod and Islands, southeast Massachusetts (Open-File Report No. 2006-1260- E). United States Geological Survey.

Stone, B.D., Stone, J.R., 2019. Geologic origins of Cape Cod, Massachusetts; Guidebook for the Northeast Friends of the Pleistocene (Massachusetts Geological Survey Open-file Report No. 19– 01).

Stone, B.D., Stone, J.R., DiGiacomo-Cohen, M.L., 2006. Surficial geologic map of the Salem Depot-Newburyport East-Wilmington-Rockport 16-quadrangle area in northeast Massachusetts (Open File Report No. 2006-1260- B). United States Geological Survey.

Stone, B.D., Stone, J.R., DiGiacomo-Cohen, M.L., Kincare, K.A., 2012. Surficial geologic map of the Norton-Manomet-Westport-Sconticut Neck 23-quadrangle area in southeast Massachusetts (No. Open-File Report 2006–1260–F). United States Geological Survey.

Stone, B.D., Stone, J.R., Masterson, J.P., O'Leary, D.W., 2004a. Integrating 3-D facies analysis of glacial aquifer systems with ground-water flow models: Examples from New England and the Great Lakes Region, USA (Open-file Series No. 2004–8). Illinois State Geological Survey.

Stone, B.D., Stone, J.R., McWeeney, L.J., 2004b. Where the glacier met the sea: Late Quaternary geology of the northeast coast of Massachusetts from Cape Ann to Salisbury, in: Proceedings of the New England Intercollegiate Geological Conference, Salem, Massachusetts, B-3. p. 25.

Stone, J.R., Stone, B.D., DiGiacomo-Dohen, M., L., Mabee, S.B., 2018. Surficial materials of Massachusetts—A 1:24,000-scale geologic map database. Scientific Investigations Map 3402. https://doi.org/10.3133/sim3402

Switzer, A.D., Pile, J., 2015. Grain size analysis, in: Shennan, I., Long, A.J., Horton, B.P. (Eds.), Handbook of Sea-Level Research. John Wiley & Sons, Ltd., pp. 331–346.

Udden, J.A., 1914. Mechanical composition of clastic sediments. Bulletin of the Geological Society of America 25, 655–744. https://doi.org/doi:10.1130/GSAB-25-655

U.S. National Park Service, 2017. Physiographic Provinces - Geology [WWW Document]. URL https://www.nps.gov/subjects/geology/physiographic-provinces.htm (accessed 8.25.20).

USACE, (U.S. Army Corps of Engineers), 2012. Nantasket Beach, Hull, MA Seawall Impacts on Beach Erosion [WWW Document]. URL https://www.yumpu.com/en/document/view/49940207/nantasket-beach-hull-ma-seawall-impacts-on-beach-fsbpa (accessed 8.26.20).

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. The Journal of Geology 30, 377–392.

Wolcott, J., 1988. Nonfluvial Control of Bimodal Grain-Size Distributions in River-Bed Gravels. SEPM JSR 58, 979–984. https://doi.org/10.1306/212F8ED6-2B24-11D7-8648000102C1865D

Wolman, M.G., 1954. A method of sampling coarse river-bed material. Eos, Transactions American Geophysical Union 35, 951–956. https://doi.org/10.1029/TR035i006p00951

Woolf, D.K., Challenor, P.G., Cotton, P.D., 2002. Variability and predictability of the North Atlantic wave climate. Journal of Geophysical Research: Oceans 107, 9-1-9–14. https://doi.org/10.1029/2001JC001124

Zenkovich, V.P., 1967. Processes of coastal development. Oliver and Boyd, London.

Zervas, C.E., 2009. Sea level variations of the United States, 1854-2006 (Technical Report No. NOS CO-OPS 053). NOAA.

Table 1. General characteristics of beaches, Massachusetts, USA

Beach[1]	Tide Range (m)	Average Wave Height (m)[2]	Wave Height Standard Dev. (m)	Geomorphic Setting[3]	Dominant Source Material[4]
Salisbury	2.7	0.9	0.3	Inlet-Segmented	Coarse Stratified Deposits
Plum Island	2.7	0.9	0.3	Inlet-Segmented	Coarse Stratified Deposits
Rockport	2.7	1.8	1.0	Headland-Separated	Till
Nahant	2.8	0.8	0.2	Headland-Separated	Fine Stratified Deposits
Revere	2.8	0.8	0.2	Headland-Separated	Fine Stratified Deposits
Nantasket	2.8	0.8	0.2	Headland-Separated	Till
Peggotty	2.7	0.9	0.6	Headland-Separated	Mixed
Humarock	2.8	0.9	0.6	Headland-Separated	Mixed
Marshfield	2.8	0.8	0.6	Headland-Separated	Mixed
Plymouth	2.9	0.7	0.6	Mainland-Segmented	Coarse Stratified Deposits
Surf	0.6	0.7	0.4	Mainland-Segmented	Mixed
Low	0.9	1.8	0.9	Mainland-Segmented	Coarse Stratified Deposits
Miacomet	0.9	1.7	0.8	Mainland-Segmented	Coarse Stratified Deposits
Town	0.6	0.6	0.3	Mainland-Segmented	Mixed
Sylvia	0.6	0.6	0.3	Mainland-Segmented	Mixed
Barges	1.0	1.2	0.6	Headland-Separated	Till
East	1.1	1.2	0.6	Headland-Separated	Till
Horseneck	1.1	1.2	0.6	Headland-Separated	Till

[1] Study sites at Rockport, Nahant, and Plymouth are referred to colloquially as “Long Beach.” The study site at Marshfield aggregates the coast between Rexhame Beach and Brant Rock and includes Fieldston Beach. We instead refer to these by their respective municipalities.

[2]Average significant wave heights along with standard deviations for the 18 sites over model simulations for years 2014 through 2016 where simulations are available every hour over this interval; data taken from nearest deep-water grid cell (i.e. depth>Lo/2)(Warner and others, 2010).

[3]From FitzGerald and van Heteran, (1999).

[4]Coarse stratified deposits = glacial outwash, delta deposits; fine stratified deposits = fine-grained glacial marine sediments; till = derived from ground moraine or erosion of drumlins; mixed = combination of two source materials, glacial till and coarse stratified deposits in various proportions.

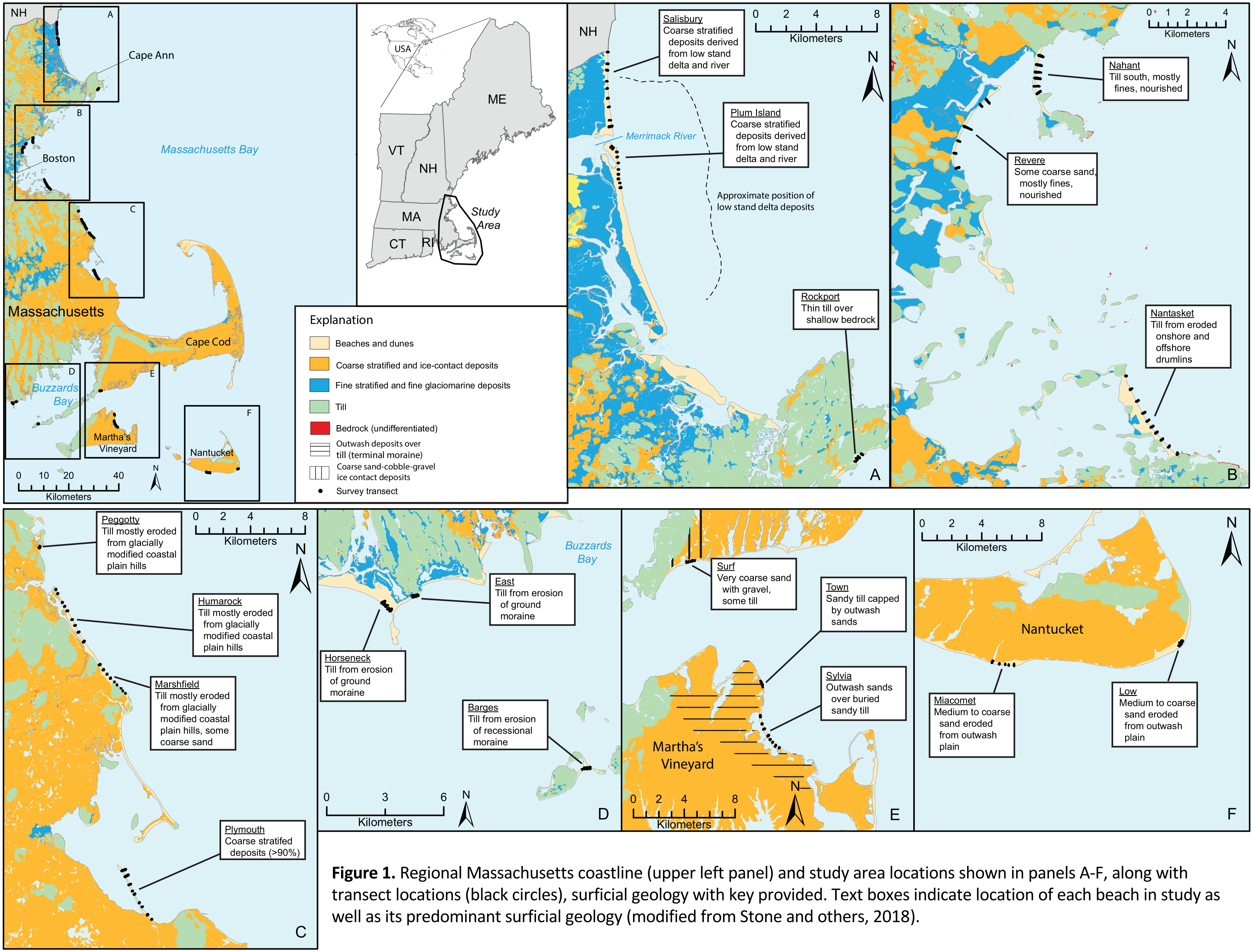

Figure 1. Regional Massachusetts coastline (upper left panel) and study area locations shown in panels A-F, along with transect locations (black circles), surficial geology with key provided. Text boxes indicate location of each beach in study as well as its predominant surficial geology (modified from Stone and others, 2018).

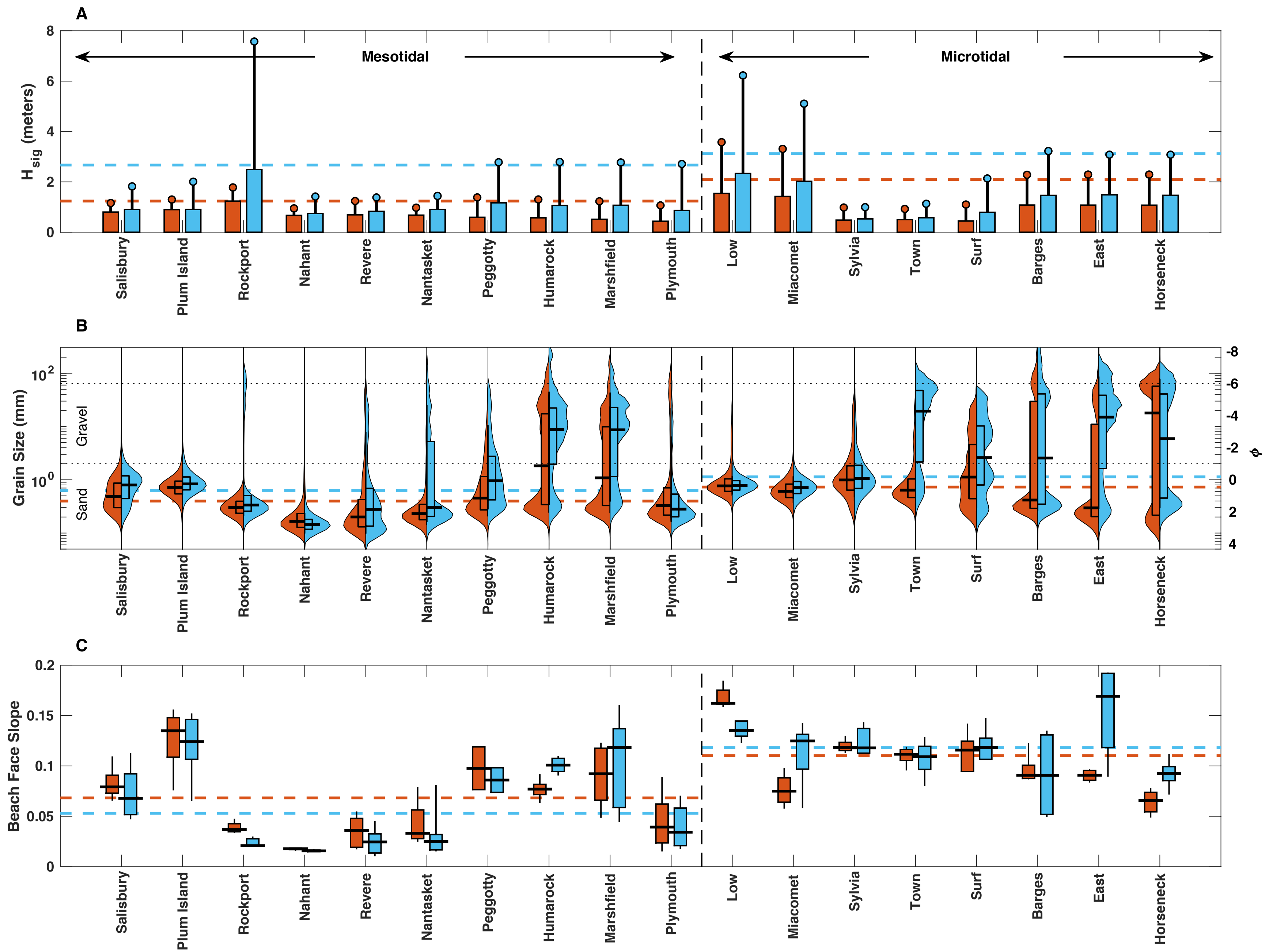

Figure 2: (A) Significant wave height - H_{sig}, and (B) combined grain size and (C) beach face slope distributions for summer (orange) and winter (blue) surveys. Beach sites arranged north-to-south (left-to-right). H_{sig} averages (bars) and 12-hr averaged maxima (circles) are over the 30-days prior to surveying. Box plots in B and C include the median (thick horizonal line), bounds of middle quantiles (boxes) and 10th-to-90th percentiles (thin vertical line). Summer and winter average 12-hr maxima and median grain size and slope for meso- and micro- tidal regions shown as dashed horizonal orange and blue lines, respectfully.

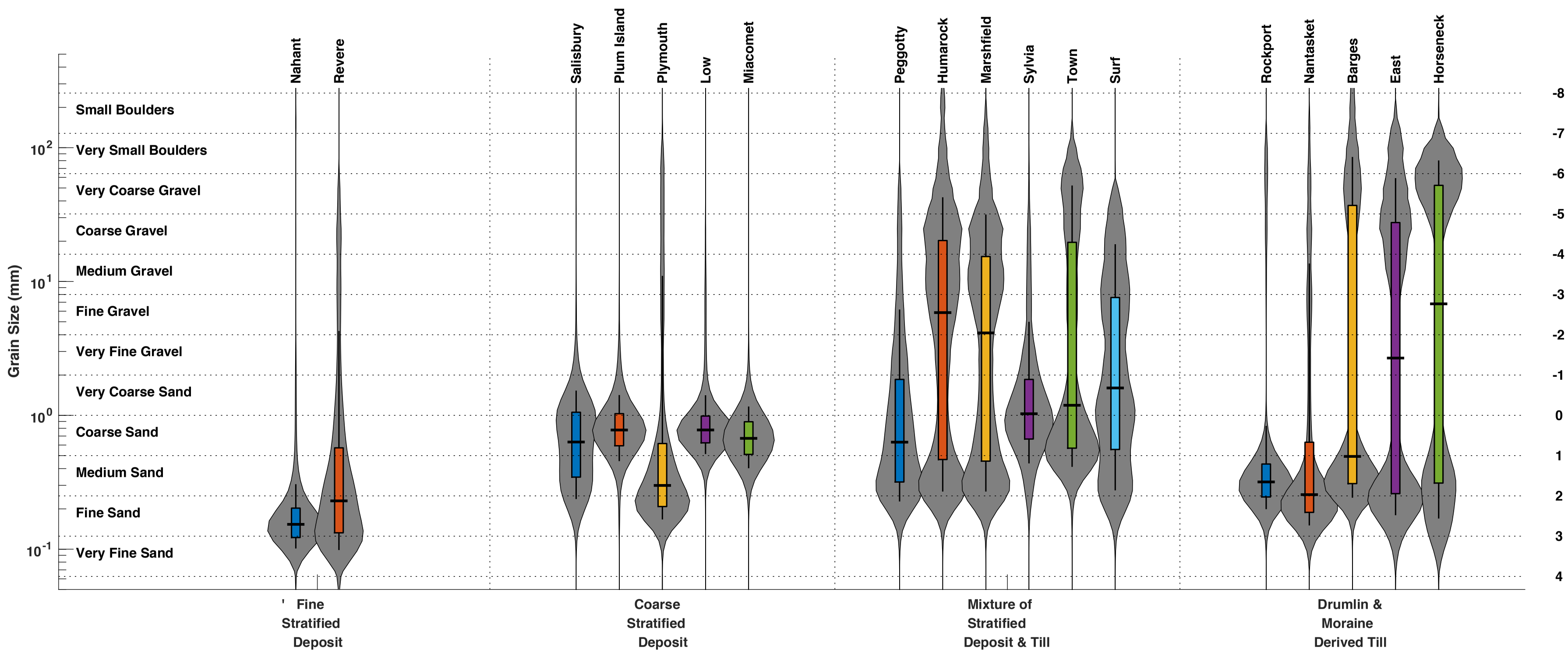

Figure 3: Bulk grain size distribution for sites and arranged with respect to their predominant sediment source. Box plots include the median (thick horizonal line), bounds of middle quantiles (boxes) and 10th-to-90th percentiles (thin vertical line).

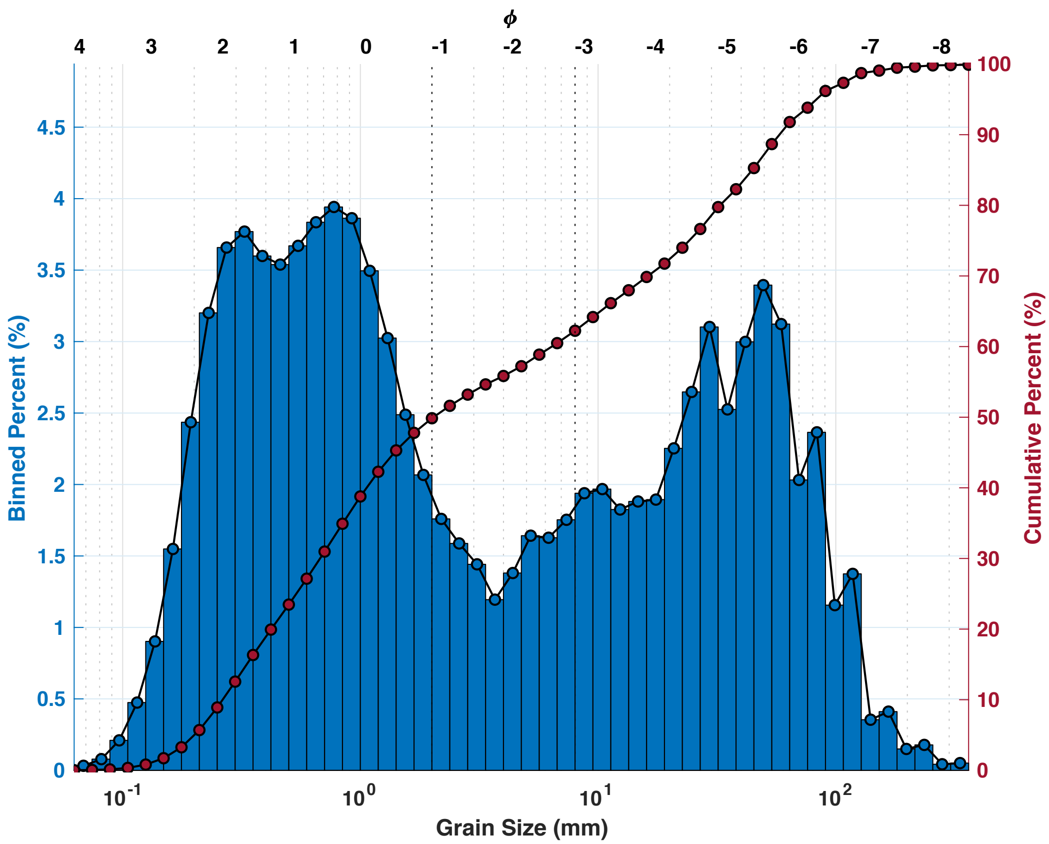

Figure 4: Composite grain size distribution of binned (blue) and cumulative (red) percent for all intertidal mixed sand and gravel samples (MSG). Here MSG samples are defined as greater than 5% of distribution exceeding 2 mm (n=454).

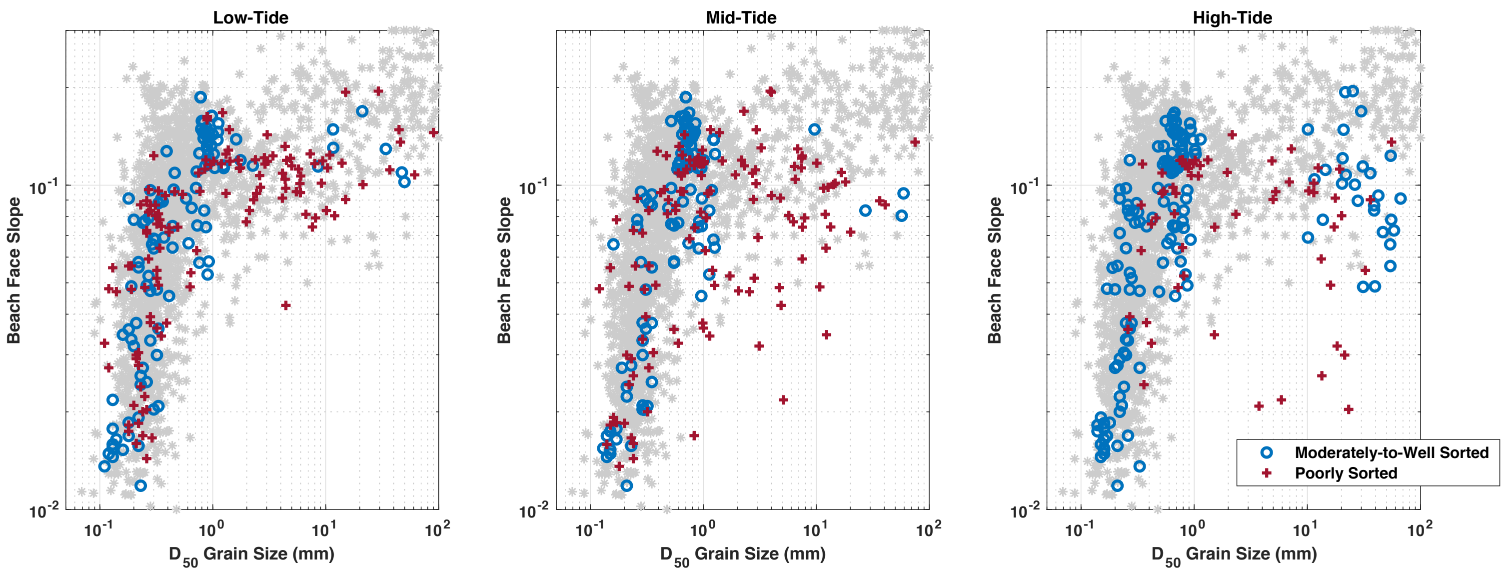

Figure 5: Median (D_{50}) grain size versus beach face slope for low tide (left panel), mid tide (middle panel) and high tide (right panel) compared to the global data set of Bujan et al. (2019). Moderately-to-well sorted samples (circles) and poorly sorted samples (plus markers) are defined by criteria presented by Blott and Pye (2001) . The same global data set from Bujan et al. (2019) is shown in each panel (gray asterisk) where grain sizes represents either a D_{50} or mean and were obtained by a variety of methods provided by references therein.

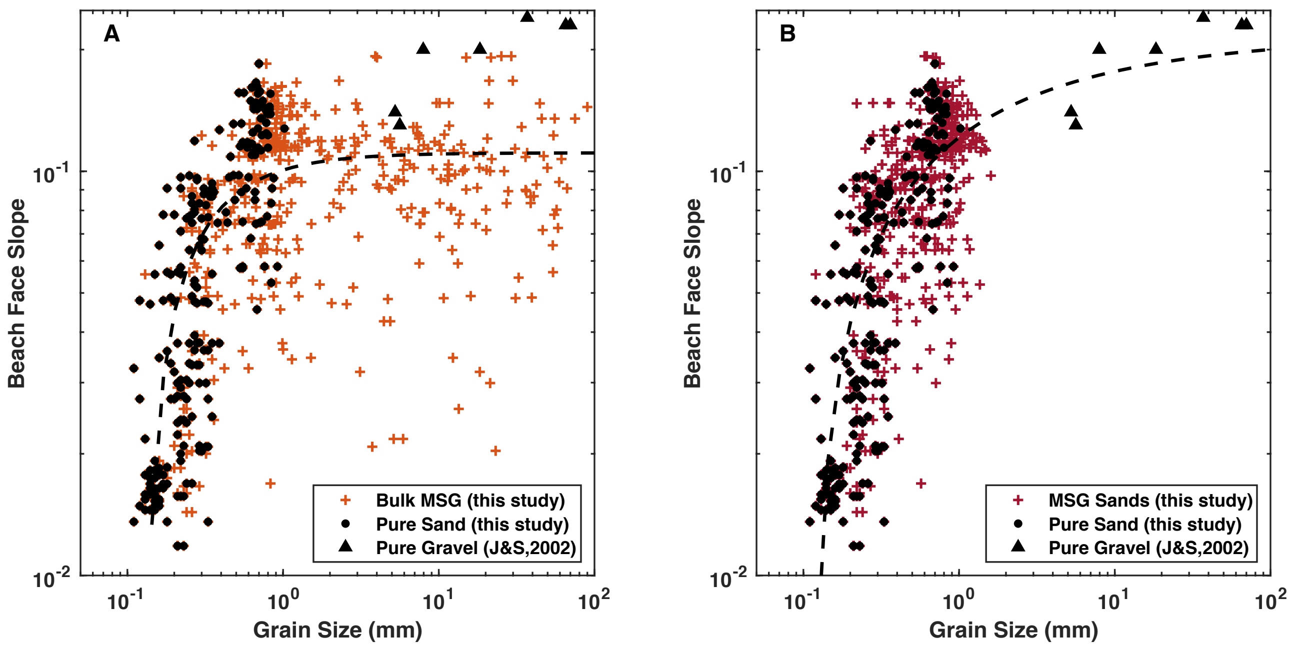

Figure 6: (A) Median grain size versus beach face slope for MSG (plus signs) and pure sand beaches (black circles) in this study compared to data by Jennings and Schulmeister (2002) for pure gravel beaches (J&S,2002, black triangles). Left panel is bulk D_{50} grain size and right panel is the median grain size of just the isolated sand fraction (i.e. median for distribution < 2 mm). Power law fits (dashed lines) are provided for bulk D_{50} and median size in sand fraction (Ds_{50}) versus beach face slope (S). Values of best fit for right panel in the form of $S=a*Ds_{50}$^b+c and fitted parameters of a = -0.10, b = -0.37, and c = 0.22.

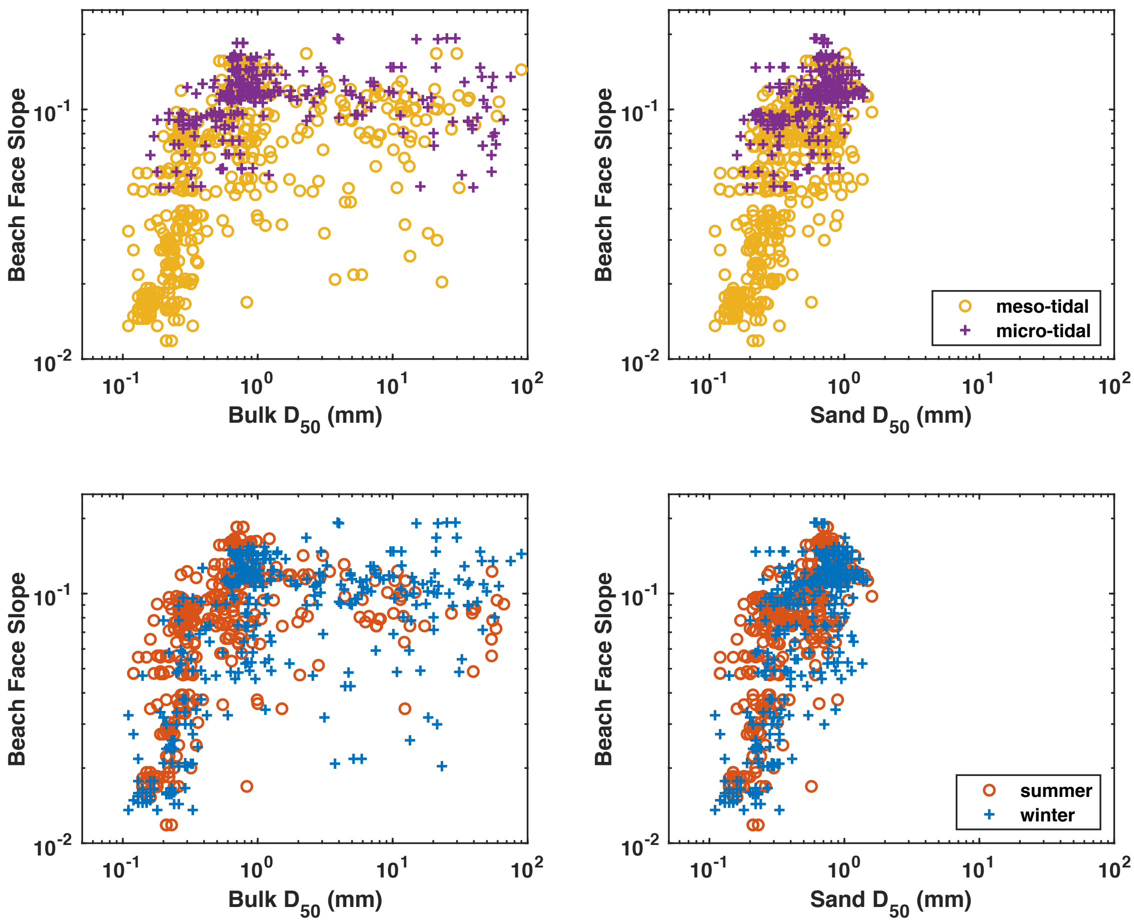

Figure 7: Beach face slope versus bulk median grain size (left panels) and median grain size for sand fraction (right panels) categorized by tidal region (top panels) and season (bottom panels).