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Grain size and beach face slope on paraglacial beaches of New England, USA

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ABSTRACT

New England lies at the boundary between the Mid-Atlantic coastal plain and paraglacial lowlands. Beaches in this region are commonly composed of a mixture of sand and gravel, but how grain size distributions relate to beach face morphology remains unclear. To fill this important knowledge gap approximately 100 paired summer and winter transects of beach face slope and intertidal grain size are examined from 18 separate beaches in southern New England from meso- and micro- tidal regimes. Paraglacial materials provide the principal local sediment source to a majority of 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 sources 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 and 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. However, where gravel mixes with the sand and bulk D_{50} increases beyond ~1 mm there is little relation between slope and median grain size. This finding is consistent with previous trends observed in global beach data sets and highlights predictable limits of using bulk D_{50} to describe bimodal systems. Upon ignoring the gravel component from the grain size distribution and recomputing median grain size for the remaining sand fraction, the familiar positive relationship between grain size and slope reemerges. Results extend globally to the large subset of beaches composed of a mixture of sand and gravel and support sand characteristics as the predominant control on slope for these mixed systems.

1. Introduction

Beaches constitute approximately 31% of the world's ice free shorelines (Luijendijk et al., 2018) and provide a multitude of benefits including a diverse array of ecological functions, 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), sediment 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., 1995; 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 control 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 pioneering study on this topic (Bascom, 1951). Five tenets of sandy 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 location, 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 offshore, 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.

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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 (tenet 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 (tenet 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 zones 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 beach zone, the zones themselves follow more than one distribution, defying the ranking of zones by the degree of sorting (tenet 3). Regarding wave state and cross-shore morphology described in tenet 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 tenet 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 drift-aligned beaches. For Southern New England, USA, 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 Shulmeister (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.

Bimodality is a common grain size characteristic for the mixed sand and gravel (MSG) beaches identified by Jennings and Shulmeister (2002). For these MSG cases predominant peaks in sand and gravel are often separated by a grain size gap centered between 0.5 and 4 mm that is likely inherited from sourcing materials (e.g. Bergillos et al., 2016; Folk and Ward, 1957; Horn and Walton, 2007; McLean, 1970; McLean and Kirk, 1969; Pontee et al., 2004). Although not evaluated specifically for MSG beaches in New England, bimodality is common to glacial deposits upon which such paraglacial shorelines are sourced (e.g. Dreimanis and Vagners, 1971; Easterbrook, 1982; Pratt and Schlee, 1969). Bimodality is also a characteristic of river deposits (e.g. Dade and Friend, 1998; Dingle et al., 2020; Eynon and Walker, 1974; Jerolmack and Brzinski, 2010; Lamb and Venditti, 2016; Maizels, 1993; Rădoane et al., 2008; Sambrook-Smith, 1996; Sambrook-Smith and Feruson, 1995; Wolcott, 1988) and by extension glacio-fluvial systems.

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) and the Mediterranean (e.g. Bergillos et al., 2017; Grottoli et al., 2017), 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 the United States from its northern border with Canada 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 regional analyses on grain size and beach slope characteristics have not emerged here. For example, of the 2144 measurements of beach slope and median grain size synthesized in a recent global compilation focused to MSG systems (Bujan et al., 2019), no data are available for the Northeastern US.

This study is focused on 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). 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; Fenneman, 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 geologic 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. For the north shore of Massachusetts extending down to the north side of Cape Cod 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) 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). Additional details on wave conditions during this study's seasonal surveys are provided in Supplemental Material.

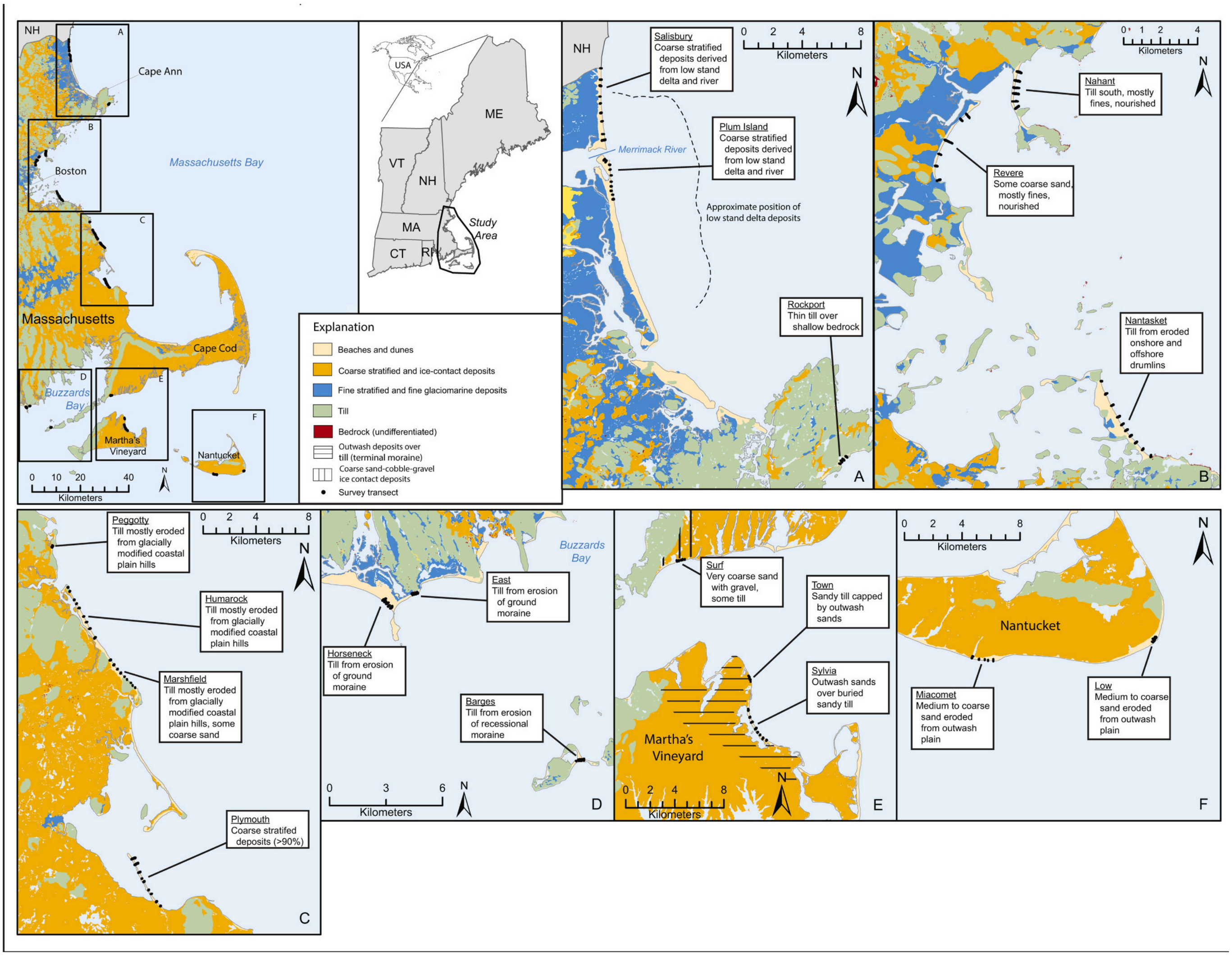

Fig. 1. Regional Massachusetts coastline (upper left panel) and study area locations shown in panels A-F, along with transect locations (black circles), surficial geology with key provided. Text boxes indicate location of each beach in study as well as its predominant surficial geology (modified from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

Eighteen beaches were investigated in this study (Fig. 1). Study site selection was guided in part in collaboration with the Massachusetts Office of Coastal Zone Management in order to target and prioritize publicly accessible sites in need of beach characterization. During this selection an emphasis was also placed on providing sufficient spatial coverage along Massachusetts' entire coastline and to target a broad suite of representative beaches observed within the region's transitional paraglacial/coastal-plain setting. A summary of the basic geomorphic, sedimentological and oceanographic conditions at each beach location is provided in Table 1 and is based on more detailed site descriptions provided in Supplemental Material.

3. Materials and methods

Beaches in this study were selected 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 1) high-tide, 2) mid-tide and 3) low-tide. When possible, additional samples were collected along storm berms and dunes (Woodruff et al., 2020), 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. Samples consisting exclusively of sand were collected in 1-l (1-quart) bags, those consisting predominantly of sand but with a minor pebble component were collected in 4-l (1-gal) bags, and mixed sand and pebble samples collected in 19-l (5 gal) buckets. Areas composed 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 subdivided into fractions greater and less than 4 mm. Distributions for grains greater than 4 mm in diameter were obtained via standard sieving techniques (Udden, 1914; Wentworth, 1922). Grain size distributions for sample fractions <4 mm in diameter 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 0 for data availability).

Inter-tidal beach elevation profiles were obtained using a Real Time Kinematic (RTK) GPS survey system or a total station survey system tied to local benchmarks, and beach face slope calculated as the elevation

Table 1
General characteristics of beaches, Massachusetts, USA.

Beach[a]	Tide range (m)	Average wave height (m)[b]	Wave height standard dev. (m)	Geomorphic setting[c]	Dominant source material[d]
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	Mixed
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	Mixed
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

[a] 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.

[b] 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 et al., 2010).

[c] From FitzGerald and van Heteren (1999).

[d] 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.

difference between high and low tide markers divided by the cross-shore horizontal distance between them. Examples of seasonal beach profiles and intertidal grain size distributions are provided in DiTroia (2019). Marker stakes were placed at the head of each transect so the transects could be reoccupied the following season. A total of 235 transects were completed.

4. Results

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

Grain size distributions at sites can be separated into either purely sand or mixed sand and gravel (MSG) systems (Fig. 2B). Tidally, no clear grain size delineations were evident between meso- and micro-tidal regions, although seasonally the winnowing of sands during the winter season generally resulted in greater predominance of gravel modes for MSG beaches (blue vs. orange in Fig. 2B). A general winter coarsening of the sand mode was also evident at some sites and was particularly evident at Horseneck.

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, respectively). This finding is consistent with past observations of beach widths generally increasing with increasing tidal range (e.g. Masselink and Short, 1993). However, as with grain size, intertidal slopes for individual beaches varied greatly relative to these regional trends 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 to or steeper than a majority of slopes for coarser MSG systems at microtidal locations (e.g. Town, Surf, Barges and Horseneck). The steepest beaches were observed 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 in a few cases during the winter the slope either steepened (e.g. Humarock, Miacomet, East, and Horseneck) or shallowed (e.g. Low). Most apparently at Horseneck, winter steepening was also accompanied by an increase in grain size for its finer sandy mode (Fig. 2B and C).

4.2. Grain size relative to surficial geology

A general winter coarsening in grain size at most study sites indicates some oceanographic control on beach characteristics (e.g. Fig. 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 remained substantially coarser (Fig. 2A and B). 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 (e.g. FitzGerald and van Heteren, 1999).

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 appeared anomalously fine due to their close proximity to off-shore sand deposits (FitzGerald et al., 1994; Smith and FitzGerald, 1994). With respect to sorting, grain size distributions obtained from beaches either partially or fully sourced by till were poorly to very-poorly sorted. In contrast, a majority of beaches sourced by stratified drift or more directly from the Merrimack River were moderately-to-well sorted.

There is a marked distinction in grain size characteristics between beaches purely sourced by stratified drift relative to those sourced in part or fully by coarser and more poorly sorted till. As noted, onshore

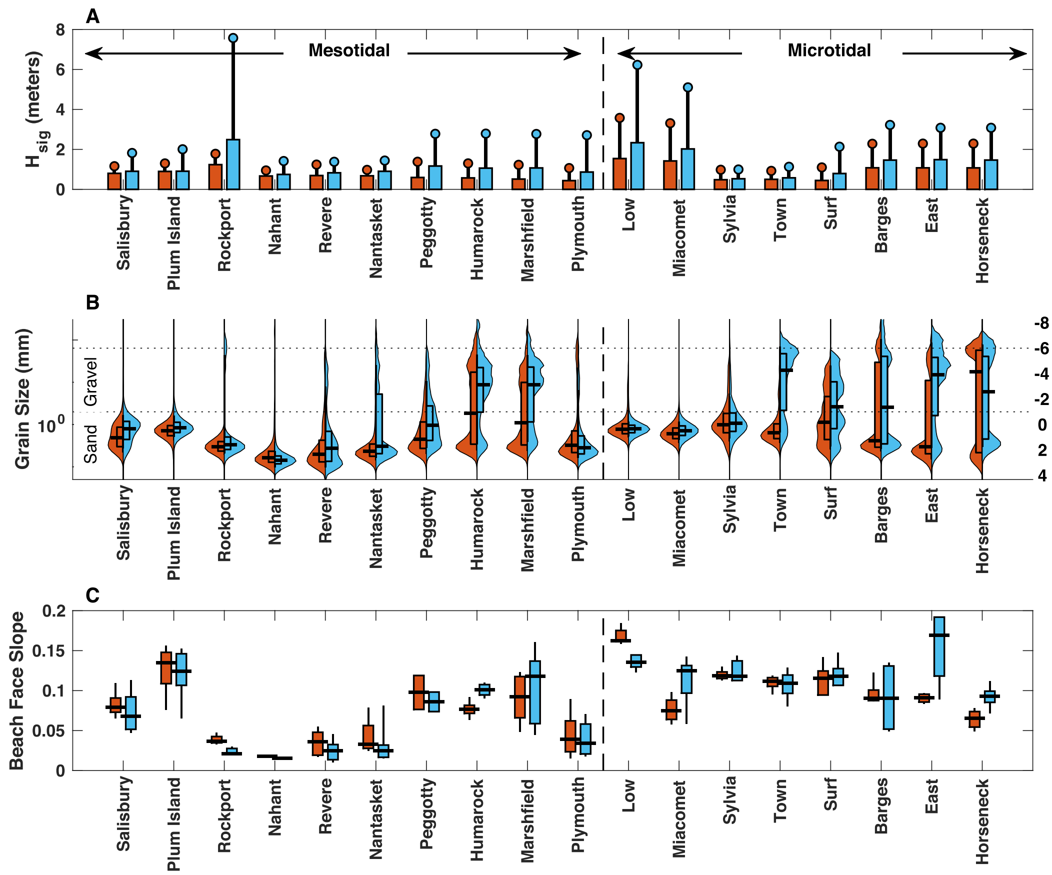

Fig. 2. (A) Significant wave height (H_{sig}) obtained from the operational Coupled Ocean-Atmospheric-Wave-Sediment Transport (COAWST) model (Warner et al., 2010), (B) combined grain size, and (C) beach face slope distributions for summer (orange) and winter (blue) surveys. Beach sites arranged north-to-south (left-to-right). H_{sig} averages (bars) and 12-h averaged maxima (circles) are over the 30-days prior to surveying (see Fig. S1 for COAWST grid locations). Box plots in B and C include the median (thick horizontal line), bounds of middle quantiles (boxes) and 10th-to-90th percentiles (thin vertical line). Seasonal PDF composite grain size distributions for each site represent the addition of obtained grain size distributions for all intertidal beach samples from the location for respective winter or summer surveys, and with bins evenly incremented at 0.25Φ (see methods for details on acquisition of individual grain size distributions). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

surficial sediments neighboring Rockport and Nantasket are predominantly till, but with glacial-fluvial sand deposits located directly offshore that likely contribute to their finer-grained distributions. 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-grained 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 that was visually evident to the south. Aside from these discussed exceptions, the predominant along-shore sediment source appears to exhibit 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 by seasonal shifts in grain size due to summer-winter changes in wave climatology illustrate secondary oceanographic control (Fig. 2).

Most grain size distributions for partially or wholly till-sourced beaches exhibit a bimodal distribution of sand and gravel (Fig. 3). The gravel mode for these systems results in overall coarser sediments when using common metrics such as the bulk median (D_{50}) or bounds of the middle quantiles (e.g. box plots in Fig. 3). However, when focused purely on the sand fraction, till-sourced systems were generally finer than the unimodal pure-sand beaches sourced by coarse stratified deposits (Fig. 3). Generally, fine stratified deposits exhibited the finest grained sand fractions, followed by pure till sourced systems and 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, consistent with the “mixed” sand and gravel beach class of Jennings and Shulmeister (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 bulk 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 and 10 mm, are therefore likely persistent features of sand and gravel beaches of southern New England rather than any artifact of comparing between disparate grain size sampling and measuring methods.

4.3. Beach face slope versus median grain size

Comparison of bulk median grain size and beach face slope data from this New England study shows general consistency with the global data set compiled by Bujan et al. (2019), (Fig. 5). Primary correspondence at

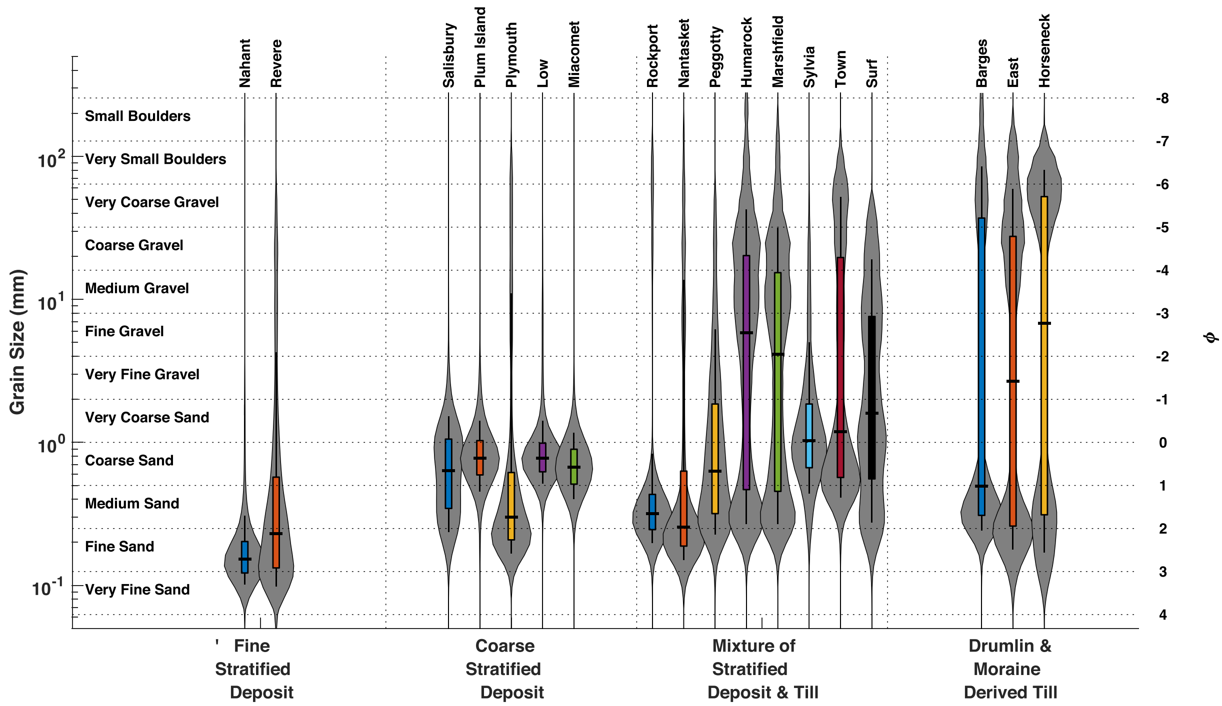

Fig. 3. Bulk grain size distribution for sites arranged with respect to their predominant sediment source. Composite PDF grain size distributions shown in gray for each site represent the addition of obtained grain size distributions for all intertidal beach samples from each respective location and with bins evenly incremented at 0.25Φ. Box plots include the median (thick horizontal line), bounds of middle quantiles (box) and 10th-to-90th percentiles (thin vertical line) for composite cumulative distribution at each site. Predominant sediment source for each site was defined based on results presented by Stone et al. (2018).

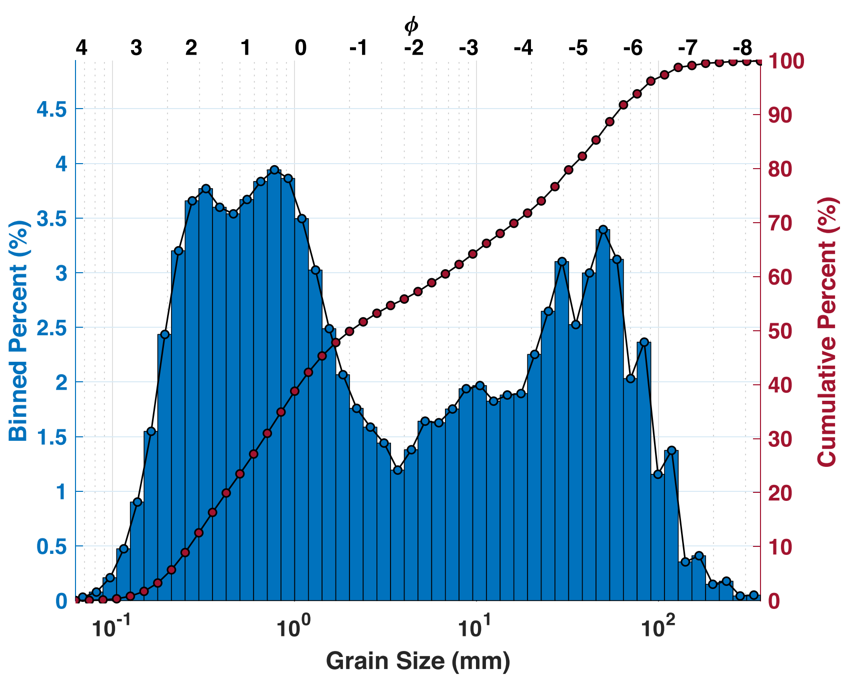

Fig. 4. Composite grain size distribution of binned (blue) and cumulative (red) percent for all intertidal mixed sand and gravel samples (MSG). Figure represents the addition of all MSG percentages for each respective grain size bin (where MSG samples were defined as having greater than 5% of their distribution in excess of 2 mm). The sum from each respective bin was then divided by the total number of MSG samples (n = 454) such that the cumulative sum of all bins equaled 100%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 bulk 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 bulk 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 slope range of 0.1 to 0.2. However, a number of slope observations beyond a bulk D_{50} of 1 mm exist well below this range in slope. Categorizing grain size measurements by their degree of sorting reveals that samples with bulk D_{50} values between 1 and 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 (Fig. S2).

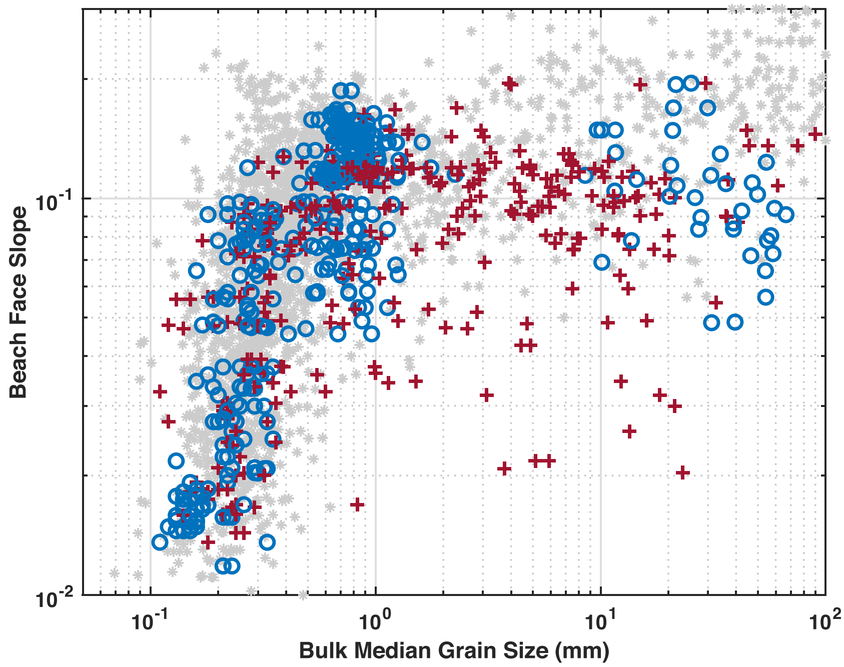

Fig. 5. Median grain size versus beach face slope for moderately-to-well sorted samples (circles) and poorly sorted samples (plus markers) as defined by the criteria of Blott and Pye (2001). Gray asterisk indicates the global data set from Bujan et al. (2019) where grain sizes represent either a bulk median or mean and were obtained by a variety of methods provided by references therein.

Testing a common power-law fit to bulk D_{50} versus 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 or grain sizes greater than 2 mm in the calculation, red plus signs in Fig. 6B).

5. Discussion

Many have noted previously the likely influence 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 role 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;

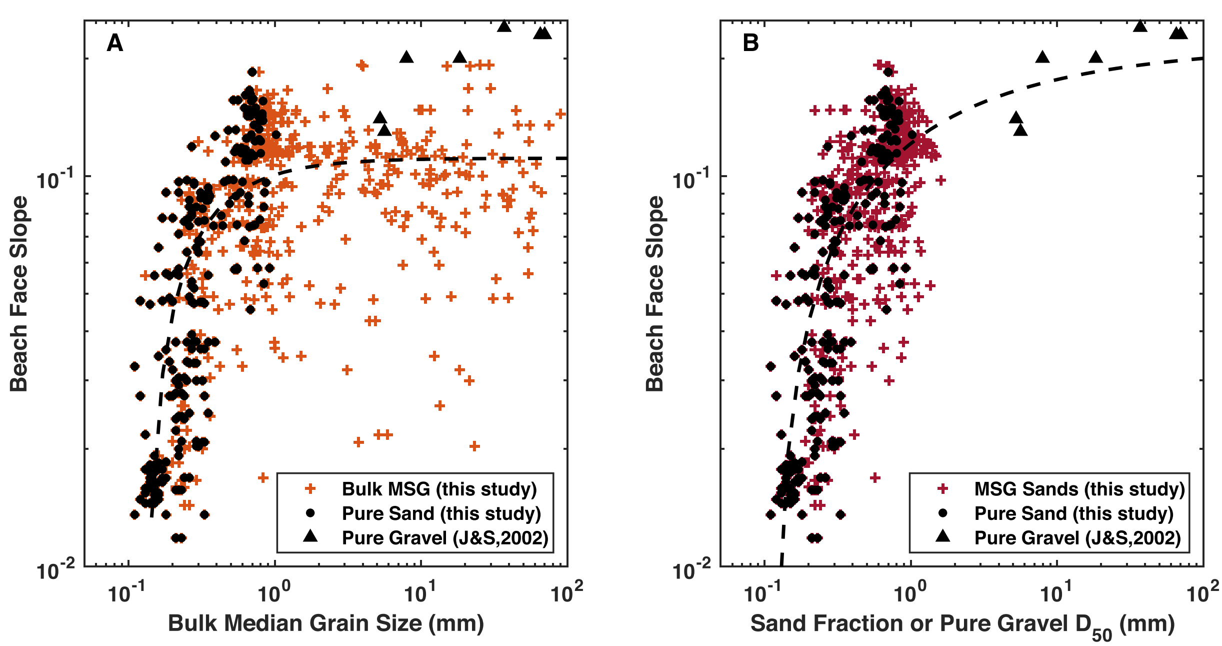

Fig. 6. (A) Bulk median grain size versus beach face slope for MSG (plus signs) and pure sand beaches (black circles) in this study compared to data by Jennings and Schulmeister (J&S) (Jennings and Shulmeister, 2002) for pure gravel beaches (Jennings and Shulmeister, 2002, black triangles). (B) Same as Panel A except plus signs now indicate median or D_{50} grain size of just the isolated sand fraction (i.e. median for distribution <2 mm). Power law fits (dashed lines) are provided for bulk median and sand fraction D_{50} versus beach face slope.

Mason and Coates, 2001; Quick and Dyksterhuis, 1994). However, although bimodality is likely common to MSG beaches (see supplemental for a more detailed discussion on origins of beach bimodality), it is still not well recognized as the reason for poor correspondence between such bulk grain size parameters as median or mean grain size and beach face slope (e.g. Bujan et al., 2019).

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). In the case of Horseneck, the earlier noted winter coarsening of this beach's sand mode could also help to explain the observed winter steepening in beach face slope at this location (e.g. Fig. 2B and C). 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 (e.g. Bujan et al., 2019).

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, the high porosity of gravel ($D_{50} > 3$ mm) 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 porosity. Thus, the grain size of beach material should determine whether infiltration into and effusion from this 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. With increasing permeability uprush can move 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). Less shear is also required to transport grains down the beach during backwash relative to uprush, further contributing to a shallowing in slope for more impermeable beaches composed of finer sands. Following this explanation the plateau in slope beyond a median grain size of ~1 mm by Bujan et al. (2019) is likely a reflection of mixed sand and gravel bimodal systems where reduced slopes are limited by their sand component. This is in contrast to unimodal, pure-gravel beaches where a more consistent steepening is likely observed with median grain size (e.g. Fig. 6; Jennings and Shulmeister, 2002).

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. Bulk median grain size is a common metric used for predicting active beach slope for unimodal beaches, but our work supports the median being less effective when applied to bimodal mixed sand and gravel beaches (MSG). Bimodality has been observed previously for MSG beaches but caveats associated with using bulk properties are still not widely recognized. This includes attribution of bimodality for a lack of correspondence between median and/or mean grain size and slope beyond ~1 mm. 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 reveal 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.

Data availability

All data related to this paper is posted at https://doi.org/10.7275/z2rb-w469 and hosted by UMass ScholarWorks (Woodruff et al., 2020).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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