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Key Points:

- Coastal overwash morphology exhibits intrinsic scaling relationships
- Scaling laws enable comparison of morphological attributes between case examples or across morphodynamic phenomena
- Scaling laws for overwash morphology align with canonical relationships for drainage basins and alluvial fans

Supporting Information:

- Supporting Information S1
- Data Set S1
- Data Set S2
- Data Set S3
- Movie S1

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Scaling laws for coastal overwash morphology

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Abstract Overwash is a physical process of coastal sediment transport driven by storm events and is essential to landscape resilience in low-lying barrier environments. This work establishes a comprehensive set of scaling laws for overwash morphology: unifying quantitative descriptions with which to compare overwash features by their morphological attributes across case examples. Such scaling laws also help relate overwash features to other morphodynamic phenomena. Here morphometric data from a physical experiment are compared with data from natural examples of overwash features. The resulting scaling relationships indicate scale invariance spanning several orders of magnitude. Furthermore, these new relationships for overwash morphology align with classic scaling laws for fluvial drainages and alluvial fans.

1. Introduction

Overwash is a sediment transport process essential to the form and resilience of coastal barrier landscapes [*Leatherman*, 1979, 1983; *FitzGerald et al.*, 2008; *Lorenzo-Trueba and Ashton*, 2014]. Driven by storm events, overwash leaves behind distinctive sedimentary features that, although intensively studied [*Morton and Sallenger*, 2003; *Donnelly et al.*, 2006], have lacked unifying quantitative descriptions with which to compare their morphological attributes across case examples or relate them to other morphodynamic phenomena. Geomorphic scaling laws quantify how measures of shape and size change with respect to each other [*Dodds and Rothman*, 2000]—information that helps constrain predictions of future change and reconstructions of past environmental conditions [*Paola et al.*, 2009]. Here a physical model of overwash morphology yields intrinsic, allometric scaling laws involving length, width, area, volume, and alongshore spacing. Corroborative comparisons with natural washover indicate scale invariance spanning several orders of magnitude. Furthermore, these new scaling laws align with canonical scaling relationships [*Dodds and Rothman*, 2000] for terrestrial and marine drainage basins and alluvial fans on Earth and Mars. This finding suggests that disparate geomorphic systems that share common allometric properties may be related dynamically, perhaps by an influence more fundamental than characteristic (system-specific) erosion and deposition processes [*Haff*, 2010; *Houssais and Jerolmack*, 2016]. Such an influence could come from emergent behavior at the intersection of advection and diffusion [*Perron et al.*, 2009; *Houssais and Jerolmack*, 2016].

Found on every continent but Antarctica [*FitzGerald et al.*, 2008], coastal barriers are low-lying, shore-parallel, sedimentary complexes consisting of a sand or gravel shoreface, beach, and a sheltered back-barrier environment. Because barrier systems are so exposed to natural hazards, efforts to understand and anticipate how barrier coastlines respond to storm events are gaining urgency, especially where coastal development is at risk [*Nordstrom*, 2000; *Donnelly et al.*, 2006; *FitzGerald et al.*, 2008; *Rogers et al.*, 2015].

One way that barriers absorb the hydrodynamic energy of coastal storms is through overwash. When tide, surge, wave setup, and swash combine during a storm into an elevated water level that exceeds barrier height, shallow overland flow—overwash—travels across the barrier, carrying sediment with it [*Sallenger*, 2000]. Washover is the sedimentary deposit that overwash leaves behind (Figure 1a), often in the teardrop shape of a fan or "lobe"; a "throat" is a shallow, typically ephemeral drainage feature funneling into the washover apex. Over short time scales ($<10^0$ year), overwash is a prerequisite for inland flooding and constitutes a hazard [*Rogers et al.*, 2015]. Over medium time scales (10^0–10^1 years), washover plays a key role in ecomorphodynamic feedbacks, positive and negative, between sediment delivery and plant growth in dunes [*Goldstein and Moore*, 2016] and back-barrier marshes [*Walters and Kirwan*, 2016]. Over long time scales (10^2–10^3 years), overwash enables barriers to maintain their height and width relative to sea level [*Leatherman*, 1979, 1983; *FitzGerald et al.*, 2008; *Lorenzo-Trueba and Ashton*, 2014]. Preserved washover stratigraphy is a valuable natural record from which to reconstruct storm and climatic conditions in the recent geologic past [*Donnelly and Woodruff*, 2007].

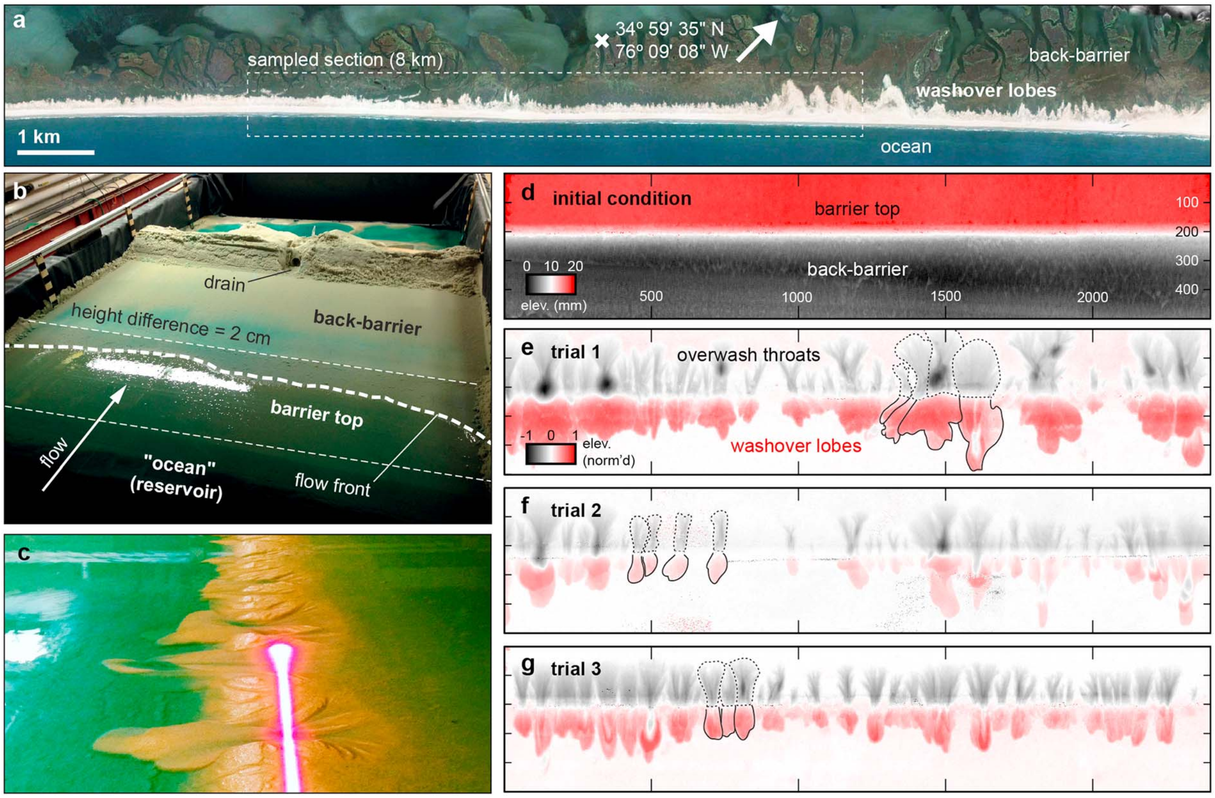

Figure 1. Barrier overwash morphology in the field and laboratory. (a) Washover lobes along an undeveloped barrier island (Core Banks, North Carolina, USA; image from 2005, via Google Earth; white arrow indicates north). (b) Experimental apparatus and design used to generate overwash morphology in spatially extended series. (c) Scanning back-barrier features with a topographic laser. (d–g) Uniform initial condition of experimental barrier and resulting patterns of overwash morphology (three trials). Units are in millimeters; in Figures 1e–1g, topographic change is normalized relative to maximum deposition across all three trials. Representative throats (dotted) and lobes (solid) are outlined to illustrate how features were delineated for measurement (see also Text S1 and Figure S1 in supporting information).

This paper presents a set of scaling laws that quantify systematic ways in which different dimensions of overwash morphology change relative to each other. (Attributes that change at different rates are considered allometric.) Morphometric scaling is useful for examining and interpreting landscape patterns that differ in setting and time and for constraining predictions of morphodynamic change—even when the specific physical mechanisms through which those scaling relationships arise are ambiguous [*Kirchner*, 1993; *Dodds and Rothman*, 2000; *Straub et al*., 2007; *Paola et al*., 2009; *Edmonds et al*., 2011]. Unifying quantitative relationships that compare basic attributes of size and shape in landscape morphology can help link three-dimensional forms with physical insight into the dynamical processes that create them.

Scaling laws for drainage patterns in terrestrial landscapes are now canonical [*Dodds and Rothman*, 2000]. Coastal engineering has produced scaling laws for the cross-shore hydrodynamics of overwash flow [*Van Rijn et al*., 2011], but a comprehensive set of equivalent relationships for overwash morphology has not been formalized [*Morton and Sallenger*, 2003; *Rogers et al*., 2015]. Overwash morphology is diverse [*Hudock et al*., 2014], and many argue that its characteristics are highly contextually dependent [*Morton and Sallenger*, 2003; *Matias et al*., 2012]. However, the findings here suggest that scaling laws in overwash morphology not only transcend the particulars of physical settings but also fall within the ranges of fundamental scaling relationships from terrestrial and submarine drainage basins to alluvial fans and deltas.

To investigate the development of overwash morphology, a physical experiment with a spatially extended aspect ratio was designed to generate trains of overwash throats and washover lobes alongshore (Figures 1b–1g and Movie S1 in supporting information). The long, low, flat barrier allowed throats and lobes in series to initiate, compete for overwash flow, grow, merge, be abandoned, or go dormant and reactivate. Over tens of minutes, throat and lobe geometries adjusted to flow conditions and changes in local slope resulting from coupled barrier erosion and back-barrier deposition. Competition for available flow meant pairs of throats and lobes grew at different rates relative to, and at the expense of, other pairs. The development of throats and lobes in series alongshore, starting from a uniform initial condition under steady forcing, reinforces recent work proposing that alongshore patterns in overwash morphology can self-organize [*Lazarus and Armstrong*, 2015]. Morphometric traits of throats and lobes (centroid position, length *l*, width *w*, area *A*, and volume *V*) were measured from topographic scans of final barrier topography (Figures 1d–1g, S1, and S2). (A full description of the experimental methods and data acquisition is available in the supporting information.)

2. Results

A measure of spatial organization applicable to both throats and lobes is their spacing ratio, calculated by convention [*Hovius*, 1996] as feature width *w* divided by cross-shore axis length *l*. Unimodal, left-skewed distributions describe the experimental spacing ratios, indicative of a predominant spatial wavelength alongshore (Figures 2a and S3). Other scaling relationships from the experimental morphology are power expressions. (These statistics, exponents, and coefficients are compiled in Table S1). Feature width *w* scales like a power of *l* (Figure 2b), as in drainage basins [*Dodds and Rothman*, 2000]. Length *l* scales like a power of area *A* (Figure 2c), after Hack's law [*Hack*, 1957] relating a river's main stream length to basin area. Lobe area scales like a power of throat area (Figure 2d), after Bull's observations [*Bull*, 1962] relating alluvial fans to their parent drainages, and is generally consistent with reported approximate conservation of mass between prestorm and poststorm barrier configurations [*Priestas and Fagherazzi*, 2010]. Measured area *A* is consistently ~70% of the calculated rectangular area ($l \times w$) (Figure S4), again as in mountain drainages [*Hovius*, 1996].

Extending Hack's law to express area as a power of volume *V* (Figure 2e) reflects that throat and lobe depths are characteristically shallow relative to their large planar areas. Extending Bull's relationship to compare lobe and throat volume shows that, like paired areas, paired volumes are nearly balanced (Figure 2f) but can vary with partial exhumation or burial of (or by) a neighboring feature (see also Text S1 and Figure S2) [*Bull*, 1962]. Volume *V* scales like a power of length *l* (Figure 2g). Effective depth (*De*) is calculated as *V/A* per feature and scales like a power of length *l* (Figure 2h). A conventional expression for washover relates volume to length in terms of volume per unit distance alongshore, calculated here as *V/w* per feature (Figure 2i).

Several of these experimental relationships can be tested with measurements from natural examples. Washover lobes along an undeveloped ~8 km segment of Core Banks (North Carolina, USA) (Figure 1a) exhibit a distribution of spacing ratios (and spacing interval) similar to that from the experiment (Figures 3a and S3). Figure 3b shows length and area measurements from the experimental lobes, Core Banks, and a sample of 118 individual washover deposits worldwide (here the "Hudock data") [*Hudock et al*., 2014]. Given measurements of Core Banks lobe area, the experimental relationship in Figure 2c predicts Core Banks lobe length to within ~21%; given Hudock lobe area, it predicts Hudock lobe length to within 24%. A scaling law from the compilation of all three data sets (experimental, Core Banks, and Hudock) is plotted in Figure 3b. (The Core Banks and Hudock data are detailed in Figure S5). Notable in this comparison is that the especially large fan on St. Joseph Island, Texas—which *Hudock et al*. [2014] conclude is an outlier and anomalous among the washover deposits they measure—appears "typical" in its allometry, despite its size, consistent with other washover features (Figures 3b and S5).

Comparisons with published measurements of washover volume per unit distance alongshore (Figures S6 and S7), calculated by sampling volume at a series of transects and dividing by the distance between transects [*Morton and Sallenger*, 2003; *Rogers et al*., 2015], suggest that this standard method of reporting volume may be more appropriate for washover terraces and sheetwash deposits [*Donnelly et al*., 2006] than for distinct lobes. The relationship between alongshore-normalized volume (m^3/m) and washover axis length in field data is reported as linear [*Rogers et al*., 2015], but in the experimental data, *V/w* scales like a power of *l* (Figure 2i). Note that the latter relation is calculated per feature; the former is not. Randomly sampling cross-shore transects of the experimental lobes from ~10% of the alongshore domain (300 transects $\times$ 3 trials) and dividing by the overall sampling interval (10 mm) collapses the experimental results into the (linear) range of previously published data. Given that both lobe volume (Figure 2g) and width (Figure 2b) scale like a power of length, the volume divided by width would be expected to scale approximately with length raised to the difference of those two powers. A related sampling distortion may affect published estimates of effective depth [*Morton and Sallenger*, 2003] (Figures 3h and S6).

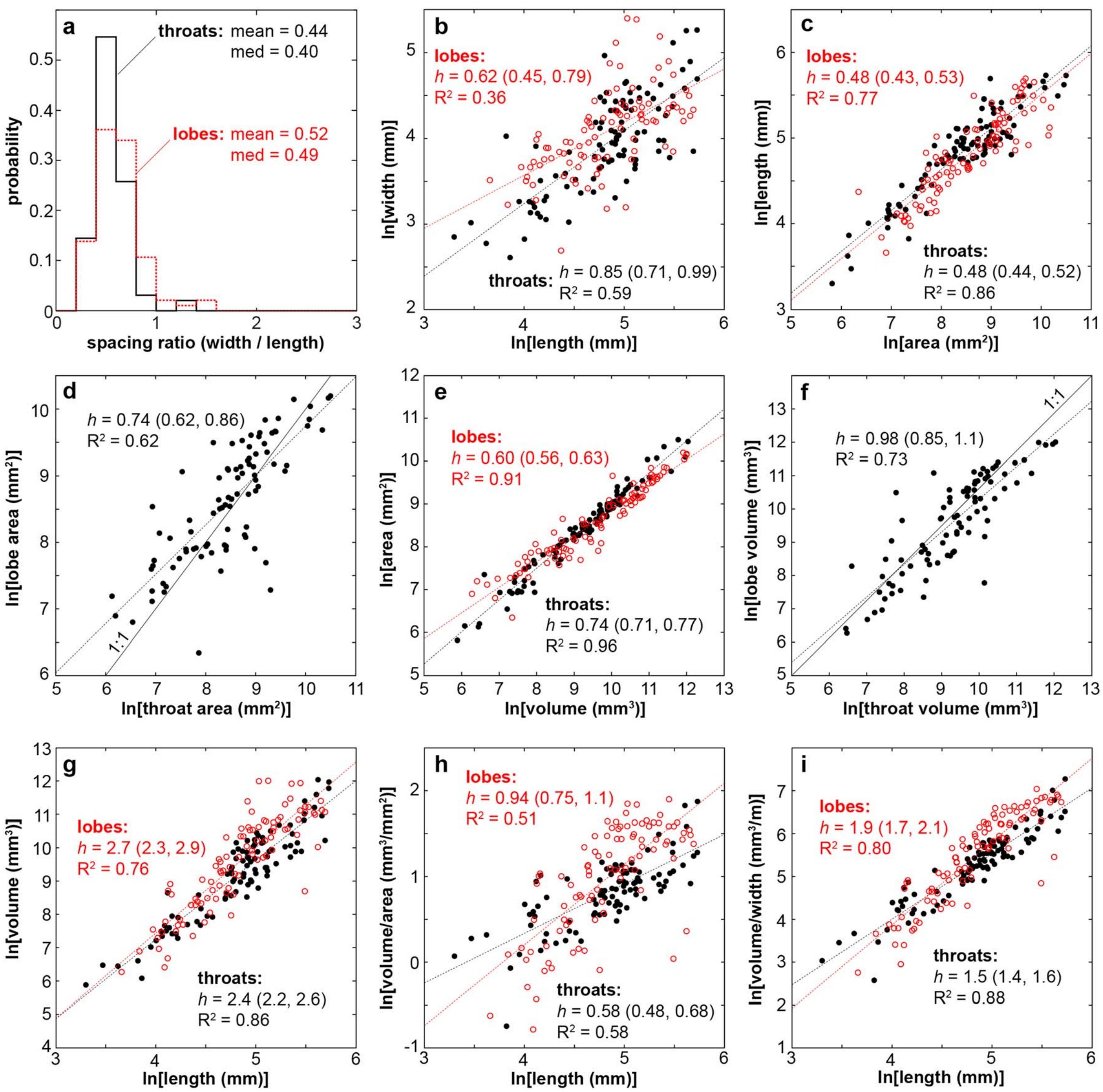

Figure 2. Scaling laws for overwash morphology. (a–i) Scaling laws for throats (filled circles) and lobes (open circles) derived from experimental overwash morphology (Figures 1e–1g). Scaling exponent h corresponds to a power expression of the general form $y = cx^h$, expressed here in natural-log transform space as $\ln(y) = h\ln(x) + \ln(c)$. The first value for h represents the best fit calculated by linear least squares regression of the natural-log transformation; values in parentheses are the 95% confidence bounds. See Table S1 for full statistical summary, including corresponding values for coefficients $\ln(c)$.

More broadly, these scaling relationships for overwash morphology may extend to other geomorphic systems with which they share geometric similarity [*Paola et al.*, 2009]. Figure 3c shows length-area scaling for the experimental and natural washover data (Figure 3b) and for depositional landforms on Earth and Mars: alluvial fans along the Po Plain of northern Italy [*Guzzetti et al.*, 1997], large alluvial fans within Martian craters [*Moore and Howard*, 2005], alluvial fans throughout Death Valley [*Bull*, 1962; *Denny*, 1965], and four scaling fits describing a set of natural and experimental deltas [*Edmonds et al.*, 2011].

Furthermore, unlike a natural barrier, where wave action tends to erase overwash throat morphology, the barrier in this experiment retained its overwash drainages. Their dimensions are useful for visualizing and estimating the "drainage basin" characteristics that overwash throats might express if left intact. Some observers of this experiment remarked that the overwashed barrier resembled a dissected linear mountain belt front with an alluvial apron [*Hovius*, 1996] (Figures 1e–1g). That resemblance is reflected quantitatively in scaling relationships. Figure 3d shows drainage length as a power of drainage area for the experimental results and several natural terrestrial and marine settings: a coarse-grained (30′ latitude/longitude) representation of

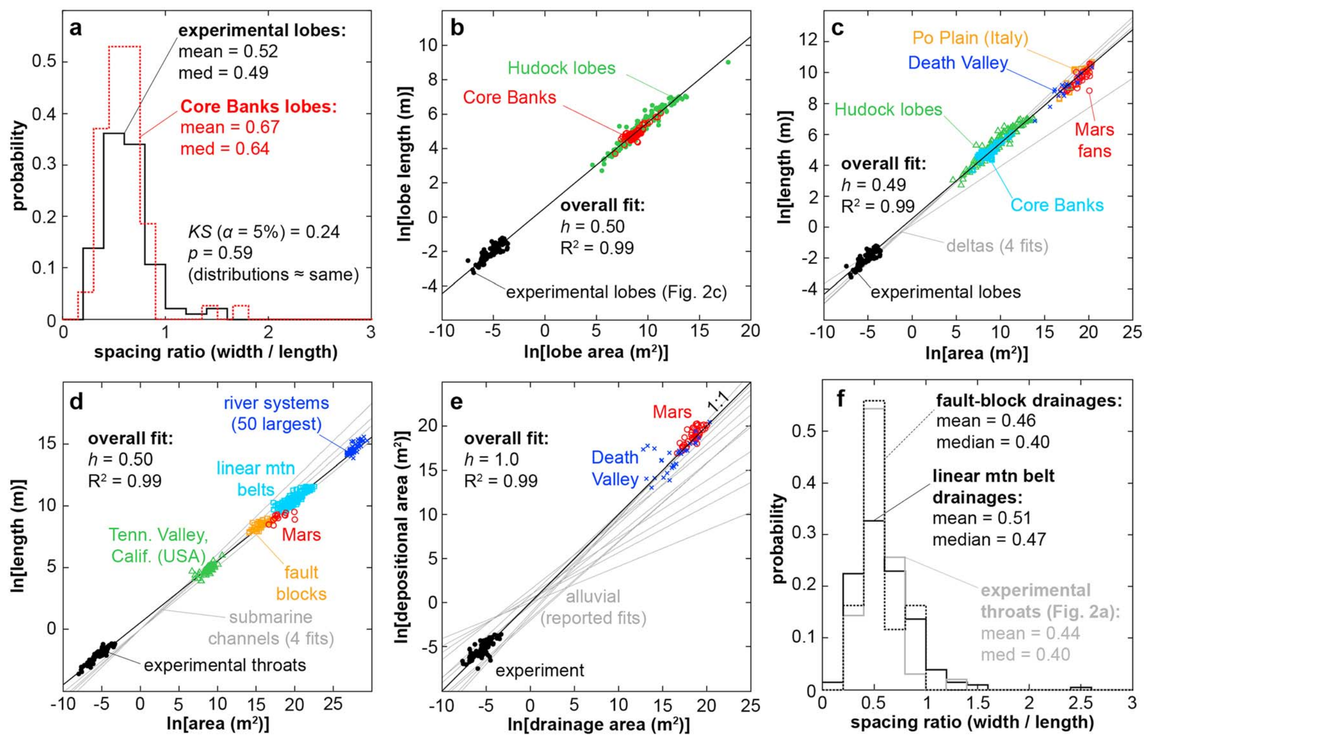

Figure 3. Comparisons of experimental data with observations from natural systems. (a, b) Scaling relationships from the experimental overwash morphology extended to data from field examples. In Figure 3a, the null hypothesis (that the experimental and Core Banks spacing ratios could have come from the same continuous distribution) of a two-sample Kolmogorov-Smirnov test is accepted at the $\alpha = 5\%$ significance level; asymptotic value p (= 0.59) is the probability of observing a test statistic $KS \geq 0.24$. The Core Banks and Hudock data in Figure 3b are detailed in Figure S5; the (Hudock) data point in the upper right corner is the washover fan at St. Joseph Island, Texas. (c–f) Scaling relationships for experimental and natural overwash morphology in the context of other depositional and erosional systems. As in Figure 2, scaling exponent h corresponds to a power expression of the general form $y = cx^h$, expressed in natural-log transform space as $\ln(y) = h\ln(x) + \ln(c)$. The first value for h represents the best fit calculated by linear least squares regression of the natural-log transformation; values in parentheses are the 95% confidence bounds. See Table S1 for statistical summary, including corresponding values for coefficients $\ln(c)$ and Table S2 for data sources.

the 50 largest river systems on Earth [*Vörösmarty et al.*, 2000], linear mountain belt fronts [*Hovius*, 1996], "alcoves" draining the interiors of Martian craters [*Kraal et al.*, 2008], drainages within fault blocks (spatial scales smaller than mountain belts) [*Talling et al.*, 1997], source area basins above channel heads in Tennessee Valley, California [*Montgomery and Dietrich*, 1989], and fits describing four large submarine channel systems [*Straub et al.*, 2007].

The paired areas of experimental throats and lobes also fall within the scaling range documented for paired drainage and alluvial areas in natural fan systems (Figure 3e) on Earth [*Bull*, 1962; *Denny*, 1965; *Church and Mark*, 1980] and Mars [*Moore and Howard*, 2005; *Kraal et al.*, 2008], and the spacing ratio distribution of experimental throats aligns with that of drainages in linear mountain belt and fault block fronts [*Hovius*, 1996; *Talling et al.*, 1997] (Figure 3f).

3. Discussion and Implications

Which barrier and storm-forcing parameters control absolute alongshore spacing in overwash morphology (Figure S3) remains an open question. Exploratory physical (Figure S8) and numerical model tests [*Lazarus and Armstrong*, 2015] suggest that relative height between the barrier top and the back barrier is an important factor. For a tall barrier, a higher volume of available sediment and a steeper slope result in larger lobes and, by extension, larger alongshore spacing. For barrier islands with back-barrier bays or lagoons, back-barrier depth may drop or surge with storm-driven "wind tides" (setup) typical of shallow basins [*Fagherazzi and Wiberg*, 2009], changing the effective back-barrier base level "felt" by washover deposition and thus affecting longer or shorter washover intrusion lengths [*Shaw et al.*, 2015]. Hydrodynamic characteristics of the storm impact scale (wave height, setup, tide, and surge) [*Sallenger*, 2000] and storm duration also inform morphological pattern formation: the former forces barrier response, and the latter allows time for morphology to organize [*Perron and Fagherazzi*, 2012; *Lazarus and Armstrong*, 2015].

Past work has proposed that trapped edge waves or hydrodynamic steering by nearshore bathymetry may be responsible for alongshore spatial patterns in overwash morphology [*Dolan*, 1971; *Dolan et al*., 1979; *Dolan and Hayden*, 1981; *Orford and Carter*, 1984]. However, the results presented here suggest the influence of dynamical self-organization, where the scaling laws are the signature of emergence [*Bak*, 1996; *Sornette*, 2006]. Self-organized patterns arising from mechanistic feedbacks between fluid flow and sediment transport have been extended to a variety of coastal morphodynamic systems [*Coco and Murray*, 2007], including bedforms and bars [*Murray and Thieler*, 2004; *Falqués et al*., 2008], beach cusps [*Werner and Fink*, 1993; *Coco et al*., 1999; *Masselink*, 1999], rip currents [*Murray*, 2004; *Calvete et al*., 2007], sand waves [*Falqués and Calvete*, 2005; *Ashton and Murray*, 2006a, 2006b], washover [*Lazarus and Armstrong*, 2015], tidal inlets [*Roos et al*., 2013], and regional-scale coastline planforms [*Ashton and Murray*, 2006a, 2006b].

The experimental data presented here are extracted from steady state topography, but information about transient morphologies [*Perron and Fagherazzi*, 2012; *Murray et al*., 2014] is retained in features abandoned by overwash flow or slowed by faster-growing neighbors. Overwash morphology may never find an equilibrium state [*Perron and Fagherazzi*, 2012]. The storm that initiates overwash may pass before local competitions for drainage area make irregular, incipient features regular [*Perron et al*., 2009]. In addition to episodic storm impacts, Aeolian transport, vegetation changes, and nearshore sediment fluxes also rework natural barrier topography. If spatial arrays of natural overwash morphology comprise a spectrum of frozen transient stages, then scaling laws that decode such transience may improve calculations of sediment fluxes and supplies required for barrier resilience [*Lorenzo-Trueba and Ashton*, 2014; *Rogers et al*., 2015].

Although these scale-invariant empirical relationships are a necessary step toward resolving the dynamics of alongshore pattern formation in overwash morphology [*Lazarus and Armstrong*, 2015], they do not demonstrate mechanism. How extreme sea levels translate into morphological change through feedbacks between fluid flow and sediment transport on the time scale of a storm event remains poorly understood [*Leatherman and Zaremba*, 1987; *Donnelly et al*., 2006; *McCall et al*., 2010; *Lazarus and Armstrong*, 2015; *Shaw et al*., 2015]. The implication that a variety of erosional and depositional landscapes, characterized by different sediment transport processes, may be related by common allometric properties (Figure 3) suggests that geomorphic behaviors at advection-diffusion transitions (and vice versa) [*Perron et al*., 2009; *Haff*, 2010; *Houssais and Jerolmack*, 2016] could be the key to disentangling mechanistic causality from acausality in physical landscape patterns [*Dodds and Rothman*, 2000; *Paola et al*., 2009].

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