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Evolution of a foredune and backshore river complex on a high-energy, drift-aligned beach

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ABSTRACT

This paper examines the multi-decadal evolution of a foredune and backshore river complex on a wave-dominated, drift-aligned coast at Wickaninnish Bay on southwestern Vancouver Island, British Columbia, Canada. Local shoreline positions are generally prograding seaward as fast as $+1.46$ m a^{-1} in response to rapid regional tectonic uplift and positive onshore sediment budgets. The northern end of the foredune system has extended rapidly alongshore in response to net northward littoral drift. Despite these net accretional responses, the beach–dune system experiences relatively frequent (return interval ~1.53 years) erosive events when total water levels exceed a local erosional threshold elevation of 5.5 m above regional chart datum. Geomorphic recovery of the beach–dune system from erosive events is usually rapid (i.e., within a year) by way of high onshore sand transport and aeolian delivery to the upper beach. This response is complicated locally, however, by the influence of a backshore river that alters spatial–temporal patterns of both intertidal and supratidal erosion and deposition.

Historic landscape changes and rates of shoreline positional change are derived from several years of aerial photography (1973, 1996, 2007, 2009, 2012) using the USGS Digital Shoreline Analysis System (DSAS). Significant volumetric changes are also estimated from aerial LiDAR-derived DEMs in 2005, 2009 and 2012, and related morphodynamics are interpreted using a statistically constrained geomorphic change detection method. Results suggest that supratidal bar development, overwash deposition and aeolian deposition on a low-lying supratidal platform, combined with alongshore extension of the foredune complex, is forcing Sandhill Creek to migrate northward in the direction of beach drift. In response, the river actively erodes (-1.24 m a^{-1}) a bluff system landward of the channel, which generates substantial sediment volumes (-0.137 m^3 m^{-2} a^{-1}) that feed a large intertidal braided channel and delta system. These local responses provide context for a conceptual model of the evolution of a wave-dominated, drift-aligned beach–foredune system that interacts with a backshore river. This model may provide useful information to local park managers as erosion and sedimentation hazards threaten visitor safety and park infrastructure.

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1. Introduction

The morphodynamics and longer-term evolution of wave-dominated coasts are shaped dominantly by erosion, deposition, and transport of sediment via high-energy wave processes and wave-generated currents (Davidson-Arnott, 2011). Coastal geomorphology in wave-dominated environments is often characterized by elongate shore-parallel sedimentary forms including longshore bars, beaches, beach ridges, and foredunes (e.g., Wright, 1977; Short and Hesp, 1982; Hesp, 2002). On such wave-dominated coasts, process-response morphodynamics typically depend on the magnitude and timing of wave energy with other forcing mechanisms such as tides, surge, and/or wind energy that control nearshore and onshore sediment transport and supply. Davies (1980) distinguishes drift-aligned coasts as those that are oriented obliquely to an incident wave approach that generates strong, alongshore sediment transport gradients. In contrast, swash-aligned coasts are oriented essentially parallel to the incident wave approach and have negligible net alongshore transport rates. On drift-aligned coasts, beach–dune morphology is the net result of alongshore alignment of beach and barrier deposits and elongate swash bars and levees that can weld to the beach and, in turn, provide an onshore sediment source for shore parallel foredune growth and establishment (Sherman and Bauer, 1993; Anthony and Blivi, 1999).

Foredune development is common on high-energy coasts with high onshore sediment supply and competent winds (Short and Hesp, 1982; Hesp, 2002). Foredune morphology can vary in complexity, height, and volume depending on a number of variables such as: i) sand supply; ii) vegetation type and density; iii) rates of aeolian deposition and/or erosion; iv) shoreline movement state (i.e. progradation or retrogradation); v) frequency and magnitude of other environmental forcing

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mechanisms (e.g., storm erosion, wave, or tidal forcing); and vi) anthropogenic impacts (Hesp, 2002). High energy, dissipative beaches typically host the largest foredunes as a result of high potential wave-induced sand transport and aeolian sand delivery to the upper beach (Short and Hesp, 1982). Compared to tidally-dominated or -modified beaches with moderate wave energy, wave-dominated beaches typically provide the largest volume of sediment necessary for dune formation. On beaches with oblique wave approach, a net alongshore drift can form nearshore and intertidal bars that can develop into an alongshore ridge that, in response to wave run-up, can grow to supratidal elevations and extend into vegetation and other debris (Carter et al., 1992). Aeolian transport and deposition on supratidal ridges or beach plains can, in turn, initiate development of incipient dunes in the backshore (Carter et al., 1992; Hesp, 2002; Anthony et al., 2006). With infrequent storm wave erosion and overwash, this incipient foredune zone can develop into an established foredune, which is distinguished by a greater height and volume of sediment and often the establishment of woody plant species (Hesp, 2002). On drift-aligned beaches, foredunes can extend alongshore and build upon former swash bars, overwash deposits, or supratidal beaches, partially in response to the preferential down-drift deposition of sediments (e.g., Wright, 1977).

River outflows on high-energy coasts and resulting sediment dispersal and accumulation in marine deltas are modified to varying degrees by wave, tide, and surge forcing (e.g., Wright, 1977; Carter et al., 1992; Cooper, 2001; Bhattacharya and Giosan, 2003; Psuty, 2004; Ashton and Giosan, 2011; Nardin et al., 2013; Anthony, 2015). More specifically, these marine processes alter fluvial outflow and associated sediment transport by: i) promoting rapid mixing and momentum exchange between river discharge and ambient waters, ii) adjusting base level and hydraulic gradient in the lower reach of the river, and iii) redistributing and reshaping river mouth morphology following initial deposition and formation of the channel. Combined littoral and aeolian activity can promote supratidal barrier development and result in a closure-breach process common to some estuarine or lagoon systems (e.g., Carter et al., 1992; Rich and Keller, 2013; Clarke et al., 2014). On high-energy coasts, however, this process may not always occur as wave energy and tidal incursions that rework the lower channel may prevent channel closure. A recent review by Anthony (2015) describes in detail the importance of wave energy in mobilizing and redistributing nearshore deposits alongshore and thereby influencing delta formation. Essentially, the spread and direction of incoming wave energy control fluvial sediment discharge patterns and, in turn, delta forms and related geomorphic processes such as shoreline progradation.

This paper examines the decadal-scale evolution of a foredune and backshore river complex on a wave-dominated, drift-aligned beach wherein process-response morphodynamics are controlled by the joint interactions between fluvial, littoral, and aeolian processes. The objectives of the paper are to: i) examine changes in historical shoreline positions from aerial photographic coverage, ii) quantify significant volumetric erosion and deposition changes within defined geomorphic units using aerial LiDAR, and iii) integrate these results with other similar studies to develop a conceptual model that describes the landscape evolution of a foredune and backshore river complex on a wave-dominated, drift-aligned coast. This model provides important information that may be of utility to coastal managers and stakeholders about potential erosion and landscape change impacts in similar geomorphic settings.

2. Study site

Wickaninnish Bay is a 10 km-wide embayment located between Ucluelet and Tofino on the west coast of Vancouver Island, British Columbia, Canada (Fig. 1). The bay is open to the Pacific Ocean and hosts four embayed, sandy beaches bound to varying degrees by rock headlands including: Wickaninnish Beach, Combers Beach, Long Beach, and Schooner Cove. Wickaninnish and Combers beaches are barred and dissipative (wide surf zone) with gradual, shallow bathymetry, mesotidal range (higher high water mean tide, HHWMT, 3.36 m above navigational Chart Datum, or m aCD), and are subject to a seasonally variable, energetic wave regime. During summer, average significant wave height (H_s) is 1.14 m and wave period (T) is 10.89 s, while the average winter H_s is 2.47 m and T is 12.07 s. Overall, Wickaninnish Bay has a maximum observed H_s of 11.44 m and T of 28.57 s. The regional wind regime is seasonally bimodal (Fig. 1, inset) and frequently competent to transport local sands with an estimated aeolian sand transport potential of 9984 $m^3\ m^{-1}$ (beach width) a^{-1} (Beaugrand, 2010). The dominant mode in the wind regime results from strong SE storm winds in the winter months, however, these winds often occur with intensive precipitation, which limits aeolian transport. Winds associated with a more moderate summer mode from the WNW appear to be more geomorphically effective, as reflected in blowout and transgressive dune alignments at Wickaninnish Bay. Combined with a high onshore sand supply, this wind regime produces very dynamic beach, foredune, and landward transgressive dune systems in the region.

Periodic erosive water levels are an integral part of beach–dune morphodynamics in the study area. Frequent dune scarping indicates that high water events capable of exceeding the elevation of the beach–dune junction occur often. Using four cross-shore monitoring profiles, Beaugrand (2010) derived a local erosion threshold elevation of 5.5 m aCD and, based on observed water level records in the region, estimated a recurrence interval for erosive events of approximately 1.53 years. Despite frequent erosion, foredunes along Wickaninnish Bay are prograding seaward by as much as $+1.5\ m\ a^{-1}$ (Heathfield and Walker, 2011), partly in response to rapid regional tectonic emergence in the region (discussed below) but also in response to high nearshore sand supply and rapid dune rebuilding at the site.

Elevated total water levels (TWL) capable of beach–dune erosion are driven by three forcing mechanisms: storm surge, wave run-up, and regional manifestations of known climatic variability (CV) phenomena, such as the El Niño Southern Oscillation (ENSO) and the longer term Pacific Decadal Oscillation (PDO). At Wickaninnish Bay, 61.5% of historical erosive events were driven principally by high stage wave energy, followed by 21.8% resulting from enhanced storm surge events (Heathfield et al., 2013). Regionally, recent research has identified strong associations between the magnitude of environmental forcing mechanisms and known ocean–atmosphere CV phenomena, such ENSO and the PDO, as well as the intensity of the Aleutian Low Pressure System (e.g., Ruggiero et al., 2001; Allan and Komar, 2002, 2006; Barrie and Conway, 2002; Abeysirigunawardena and Walker, 2008; Heathfield et al., 2013). For example, the ENSO phenomenon, which ultimately results in warmer sea surface temperature (SST) in the equatorial eastern Pacific, can trigger varying regional and distal changes in weather phenomena (i.e., teleconnections) along the western coast of North America. This can result in regional-scale manifestations of CV events including enhanced storminess. Contrary to several articles (e.g., Crawford et al., 1999; Storlazzi et al., 2000; Subbotina et al., 2001; Allan and Komar, 2002) that identify El Niño as an important driver of erosion on the western coast of North America, Abeysirigunawardena et al. (2009) and Heathfield et al. (2013) found a stronger correlation between the cold La Niña phase and storm activity on western Vancouver Island. Essentially, this results from a shift in storm tracks toward the southern coast of British Columbia and the northern coast of Washington during La Niña events (Heathfield et al., 2013: Fig. 6).

Regional geology also exerts control on beach geomorphology as local outcrops can influence nearshore currents, wave dynamics, and littoral sediment transport pathways. Tectonic uplift along the Cascadia Subduction Zone, which lies immediately offshore of western Vancouver Island, is causing crustal emergence at rates of 2.9 to 2.6 mm a^{-1}, which exceeds rates of absolute (i.e., eustatic and steric) sea-level rise in the Tofino region (1.7 mm a^{-1}) and results in a net fall of relative sea level of -0.9 mm a^{-1} (Mazzotti et al., 2008). This geological setting,

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