

Beach erosion under rising sea-level modulated by coastal geomorphology and sediment availability on carbonate reef-fringed island coasts

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ABSTRACT

This study addresses gaps in understanding the relative roles of sea-level change, coastal geomorphology and sediment availability in driving beach erosion at the scale of individual beaches. Patterns of historical shoreline change are examined for spatial relationships to geomorphology and for temporal relationships to late-Holocene and modern sea-level change. The study area shoreline on the north-east coast of Oahu, Hawaii, is characterized by a series of kilometre-long beaches with repeated headland-embayed morphology fronted by a carbonate fringing reef. The beaches are the seaward edge of a carbonate sand-rich coastal strand plain, a common morphological setting in tectonically stable tropical island coasts. Multiple lines of geological evidence indicate that the strand plain prograded atop a fringing reef platform during a period of late-Holocene sea-level fall. Analysis of historical shoreline changes indicates an overall trend of erosion (shoreline recession) along headland sections of beach and an overall trend of stable to accreting beaches along adjoining embayed sections. Eighty-eight per cent of headland beaches eroded over the past century at an average rate of $-0.12 \pm 0.03 \text{ m yr}^{-1}$. In contrast, 56% of embayed beaches accreted at an average rate of $0.04 \pm 0.03 \text{ m yr}^{-1}$. Given over a century of global (and local) sea-level rise, the data indicate that embayed beaches are showing remarkable resiliency. The pattern of headland beach erosion and stable to accreting embayments suggests a shift from accretion to erosion particular to the headland beaches with the initiation of modern sea-level rise. These results emphasize the need to account for localized variations in beach erosion related to geomorphology and alongshore sediment transport in attempting to forecast future shoreline change under increasing sea-level rise.

Keywords Beach, coastal, erosion, Hawaii, Oahu, sea-level, shoreline.

INTRODUCTION

Coastal erosion is a problem in Hawaii (Romine & Fletcher, 2012), on continental shores of the United States (Morton *et al.*, 2004; Morton & Miller, 2005; Hapke *et al.*, 2006, 2010; Hapke & Reid, 2007) and coasts around the world (Bird,

1987). Beach erosion and shoreline recession will increase on a regional to global scale with increasing sea-level rise in coming decades (National Research Council, 2012; IPCC, 2014). However, coastal scientists are limited in their ability to predict shoreline change, particularly on the scale of individual beaches and littoral

cells, because shoreline change can be dominated by localized sediment availability and transport, which can act partially or totally independently of sea-level change. Other factors complicating the ability to forecast shoreline change include alongshore and cross-shore variations in geology, lithology and coastal slope. Understanding how beaches will change in a future dominated by sea-level rise requires insights into these localized processes governing historical and modern shoreline changes.

Sea-level rise has been implicated as a driver of modern (observed) shoreline change for island coasts (Singh, 1997; Ford, 2012; Romine *et al.*, 2013) and continental coasts (Leatherman *et al.*, 2000; Zhang *et al.*, 2004; Brunel & Sabatier, 2009; Guitierrez *et al.*, 2011; Yates & Cozannet, 2012). However, the relative roles of coastal geomorphology, sediment availability, human influences and sea-level change in driving shoreline change are not well-understood and add to uncertainty in these studies. These gaps in understanding of the relative influence of individual processes on shoreline change highlight the need for further studies that rely on observational data and models and are applicable at the scale of individual beaches (Le Cozannet *et al.*, 2014).

The reef-fringed coast of Oahu, Hawaii, is typical of other carbonate shoreline systems found on tectonically stable islands in equatorial oceans worldwide. Throughout low-latitude areas of the Pacific and elsewhere, coasts have undergone a unique history of relative sea-level fall during the late Holocene due to post-glacial geoid subsidence (Mitrovica & Peltier, 1991; Mitrovica & Milne, 2002) followed by recent eustatic sea-level rise due to global warming (IPCC, 2014). Millions of people living on reef-fringed carbonate coasts around the world are exposed to increasing shoreline erosion with accelerating sea-level rise. It is critically important that coastal managers are provided with actionable scientific results that inform new policies to support decision making and planning for improved hazard resilience and resource management.

Using the Oahu coast as a representative setting for carbonate, reef-fringed coasts in equatorial waters, this study addresses gaps in current understanding of the roles that coastal geomorphology, sediment supply and sea-level rise play in shoreline changes at the scale of individual beaches. In particular, this study examines the role that coastal geomorphology and available sediment, which are typically remnants of past sea-level changes, play in alongshore variability

in beach erosion rates. Also, the implications of these findings in projecting future shoreline change under increasing rates of sea-level rise are discussed.

Historical shoreline positions and change rates from Fletcher *et al.* (2012) are utilized (see *Materials and methods* section) to analyse spatial patterns of beach erosion and to evaluate the importance of coastal geomorphology and alongshore sediment transport on observed and future coastal change. The primary focus is on beaches of north-east Oahu due to: (i) the coastal geology, which is characterized by a carbonate sand-rich strand plain (described in more detail in the *Physical setting* section) – a common feature on many tectonically stable carbonate reef-fringed volcanic and atoll islands (Grossman *et al.*, 1998; Dickinson, 2001, 2004); (ii) the relative abundance of historical shoreline positions from existing data sets (*Historical shorelines* section); (iii) the kilometres-long semi-continuous beaches with repeated headland-embayment morphology allowing for investigation of characteristic longshore and cross-shore sediment transport patterns; and (iv) the available maps of nearshore sediment deposits and bathymetry (Conger *et al.*, 2009). cursory inspection of plots of shoreline change along north-east Oahu in Fletcher *et al.* (2012) suggests a predominant trend of erosion along headland sections of beach and accretion within adjoining embayed sections of beach. In addition to analysis of spatial patterns of shoreline change, potential relationships between the observed spatial patterns of shoreline change, existing coastal geomorphology and localized changes in late-Holocene sea-level are discussed.

PHYSICAL SETTING

The island of Oahu, Hawaii, is located in the tropics of the central North Pacific (Fig. 1). The coast is fringed by a carbonate reef platform comprised of a patchwork assemblage of fossil Pleistocene reefs from interglacial high sea-level stands of the past several hundred thousand years (Fletcher *et al.*, 2008). Hawaii lies in a microtidal zone (tide range ≤ 1 m). The north-east Oahu study area is exposed to large waves in winter from the North Pacific (winter months) and predominant trade winds year-round. As a result, wave-generated currents are the primary drivers of sediment transport (Norcross *et al.*, 2003).

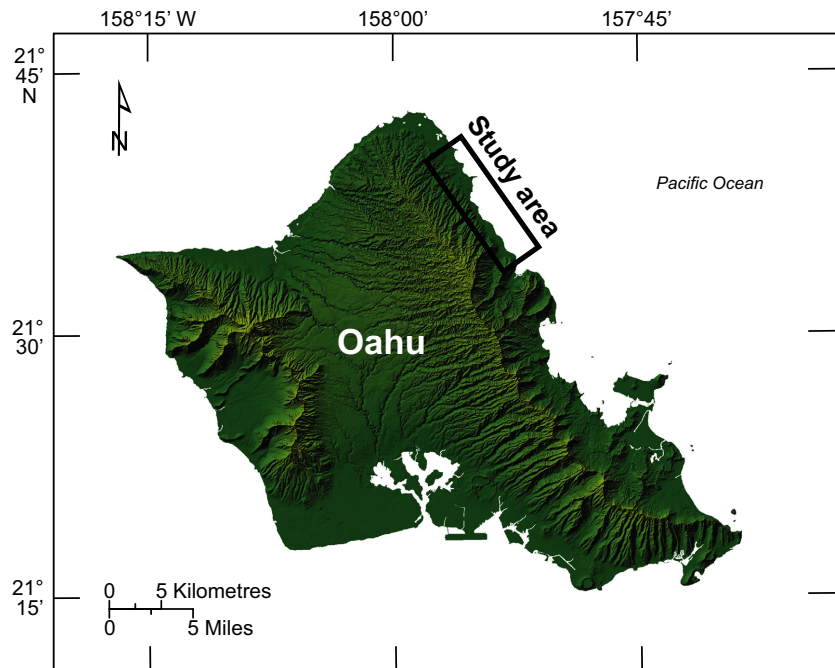


Fig. 1. Shoreline study area (black box) on the north-east coast of Oahu, Hawaii.



Fig. 2. Low-lying sand-rich coastal plain and beach at Punaluu, east Oahu (view looking south-west). Note the embayed beach fronting the channel in the nearshore reef (left) and headland beach fronting the shallower nearshore reef (right) (photograph by Andrew D. Short, University of Sydney).

Beaches along east Oahu, including the study area, are composed primarily of biogenic calcareous sand originally derived from nearshore reefs (Harney & Fletcher, 2003). Volcanoclastic sediment eroded from inland watersheds is typically a minor fraction of beach sand on Oahu. Beaches are typically backed by low-lying coastal plains comprised of a mixture of beach deposits and dunes, lithified carbonate deposits (including fossil reef, beachrock and aeolianite) and alluvium. In many locations, including

within the study area, beaches are simply the eroded leading edge of a sand-rich coastal plain (Fletcher *et al.*, 2012) (Fig. 2).

Historical shoreline studies indicate an overall stable trend (region-wide average) on beaches along east Oahu (Fletcher *et al.*, 2012; Romine & Fletcher, 2012). Like other coastal regions in Hawaii, long-term shoreline trends along east Oahu are highly variable along the shore, when examined at the scale of individual beaches and littoral cells.

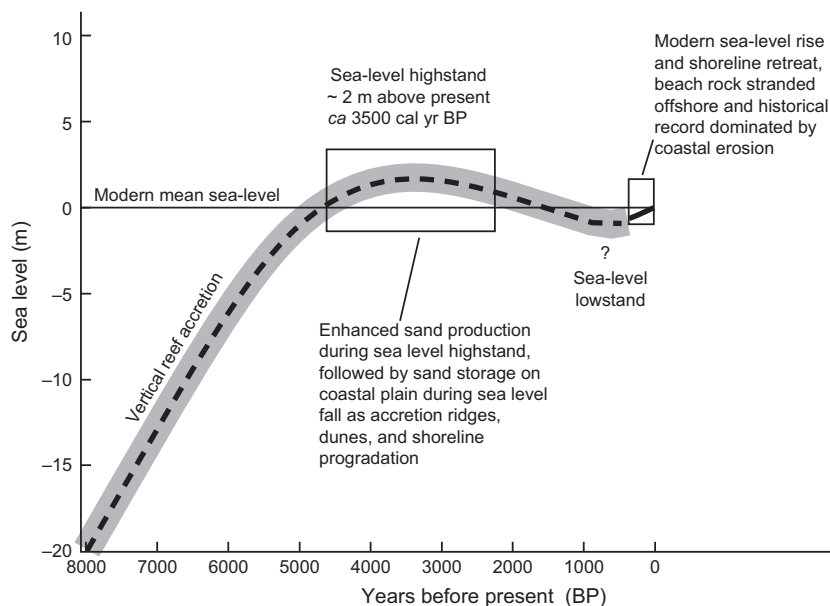


Fig. 3. Conceptual Holocene sea-level curve for Oahu indicating sea-level *ca* 2 m higher than present *ca* 3500 yr BP, followed by a period of falling sea-level prior to the initiation of modern sea-level rise observed in tide gauge records (adapted from Fletcher *et al.*, 2008).

The geomorphology of the shoreline and low-lying coastal plain around Oahu are largely a result of sea-level changes over the past several thousand years. Multiple lines of evidence, including stranded beach deposits, wave-cut notches and geophysical models indicate that sea-level stood roughly 2 m higher than present *ca* 3500 yr BP around Hawaii (known locally as the ‘Kapapa highstand’) (Stearns, 1978; Fletcher & Jones, 1996) (Fig. 3) and other ‘far-field’ sites in the Pacific (Clark *et al.*, 1978; Grossman *et al.*, 1998). This sea-level history is the result of glacial isostatic adjustment (i.e. geoid subsidence) resulting in variation in oceans in the far field of the ice sheets during the late Holocene (Mitrovica & Milne, 2002), termed ‘equatorial oceanic syphoning’ by Mitrovica & Peltier (1991). Studies of the lithology and geochronology of coastal plain and beach deposits on Oahu and neighbouring Kauai indicate a late-Holocene age [*ca* 5000 years BP (Before Present) – near present] for most carbonate sediments with few samples of sand indicating a modern origin (Harney *et al.*, 2000; Calhoun *et al.*, 2002; Harney & Fletcher, 2003). Other workers find a similar geological framework on low-latitude coasts worldwide (Grossman *et al.*, 1998; Dickinson, 2001, 2004).

Modern tide gauge records indicate sea-level rise of $1.41 \pm 0.22 \text{ mm yr}^{-1}$ on Oahu over the past century (<http://tidesandcurrents.noaa.gov/>; last viewed December, 2015). The present authors assume that modern sea-level rise was preceded by a period of falling sea-level subsequent to the Kapapa highstand (as shown in Fig. 3). The per-

iod leading up to the Kapapa highstand was characterized by invigorated marine carbonate production and deposition (Calhoun & Fletcher, 1996; Harney *et al.*, 2000; Harney & Fletcher, 2003; Grossman & Fletcher, 2004) due to increased accommodation space for reef growth and flooding of the upper coastal plain around Oahu. Sea-level fall following the Kapapa highstand resulted in an overall trend of shoreline progradation as former beach ridges were stranded on the coastal plain and developed into coastal dunes and cusped sandy headlands that shape much of the modern-day geomorphology of the low-lying sandy coastal plains.

The shoreline in the study area is characterized by two sinuous beaches, each several kilometres in length, lying atop a carbonate reef platform, with occasional outcrops of beachrock (lithified beach deposits). The beaches are characterized by a sequence of headland and embayed sections of beach (see Fig. 5 in *Results*). Embayed beaches are typically aligned with watersheds including palaeo-stream channels incised in the shallow reef platform. Cusped headland beaches are typically aligned with the shallowest portion of the fringing reef platform between channels (drowned interflaves). In most locations not fronting sand-filled channels, the base of the foreshore (beach toe) intersects with the reef with limited sand in the nearshore.

A wide shallow-crested fringing reef is typically located a few hundred metres offshore. The upper reef platform is incised by sand-filled palaeo-channels and palaeo-karst features, and

moderates open ocean wave energy reaching the shoreline. The beaches of north-east Oahu are typically narrow (10 to 30 m wide) compared with most continental settings. Numerous streams cross the coastal plain from inland watersheds, often emptying at the landward 'head' of a reef channel carved by the watershed during lower sea-levels.

MATERIALS AND METHODS

Preliminary inspection of shoreline trends along the north-east coast of Oahu from Fletcher *et al.* (2012) suggests an overall pattern of higher annual rates of erosion at headland beaches and comparatively lower rates of change at embayed beaches. This process of headland erosion and embayment infilling is a fundamental principle of coastal morphodynamics and results from concentration of wave energy (erosion) on a headland due to refraction and reduced wave energy in the embayment due to wave dispersion (deposition and accretion). However, this pattern has not been well-documented on carbonate reef-fringed tropical coasts. This study examines spatial relationships between observed patterns of shoreline change, coastal geomorphology and modern sea-level rise along a representative section of coastal strand plain at north-east Oahu, Hawaii.

Historical shorelines

Historical shoreline positions and rates of change over the past century are adapted from previous work. A summary is provided below of the methods used to measure historical shoreline change herein and also refers the reader to Fletcher *et al.* (2012) and Romine & Fletcher (2012) for more detail.

Historical shoreline changes were calculated over the past *ca* 80 years (1927 to 2006) for roughly 14 km of beach along north-east Oahu. Erosion and accretion is measured from shoreline positions digitized using photogrammetric and geographic information system (GIS) software from orthorectified aerial photographs and survey charts over the period 1927 to 2006. Ten or eleven historical shoreline positions are available within the study area, providing relatively good temporal coverage (Oahu ranges from three to twelve historical shorelines). Changes in shoreline position were measured using the software at shore-normal transects spaced approxi-

mately every 20 m along the shore. A total positional uncertainty is calculated for each historical shoreline based on studies of short-term (hourly to intra-annual) shoreline variability and errors inherent in the mapping processes. Shoreline change rates were calculated using weighted least squares (WLS) regression in the Digital Shoreline Analysis System (DSAS; Thierler *et al.*, 2009) with shoreline positional uncertainties applied as the weights so that historical shorelines with higher uncertainty have less influence on the shoreline trend.

Geomorphology

This study looks primarily at differences in shoreline trends at headland and embayed sections of beach. The headland and embayed sections of beach are distinguished through visual interpretation of historical shoreline positions in a GIS supported by numerical modelling of shoreline curvature (concavity). Shoreline curvature is modelled using Legendre Polynomials fit to historical shoreline locations (positional measurements). The polynomial shoreline model provides a continuous mathematical function that is differentiated to locate inflection points (changes in concavity), providing the boundaries between headland (convex seaward) beaches and embayed (concave seaward) beaches (Fig. 4).

Multiple overlapping shoreline models are calculated along a coast, each with length no greater than three headlands and two embayments. Limiting the individual models to such shorter sections of coast allows for an optimal fit to the historical shorelines while limiting model complexity (few model parameters, N). Shoreline models with increasing complexity (increasing N , up to a maximum $N = 20$) are calculated until the highest parameter model is identified that indicates only one inflection point between each headland and bay (head-bay boundary). Inflection points (headland/embayment boundaries) are utilized only from the central portion of each individual shoreline model to avoid any 'end effects' that result in poor fit of model shorelines near their extremities.

Statistical analysis

Erosion rate uncertainties from Fletcher *et al.* (2012) were calculated at the 95% confidence interval (CI, 2-sigma). The present study recalculated rate uncertainties at the 80% CI due to the

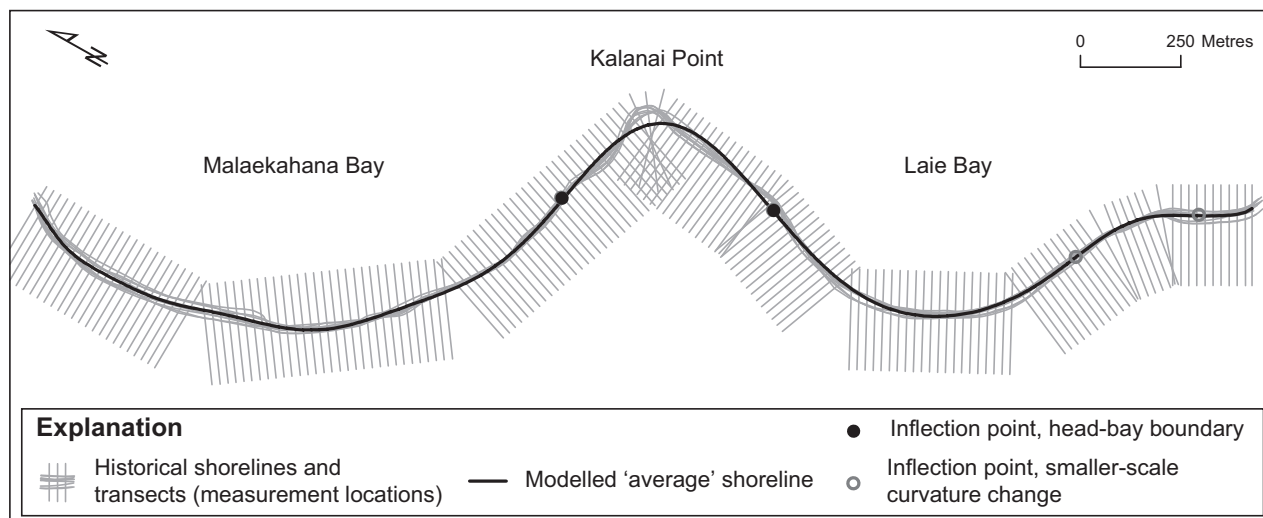


Fig. 4. To delineate boundaries between headland and embayed sections of beach, a polynomial shoreline model (Legendre Polynomial, black line) is fit to historical shoreline positions (grey shorelines) using least squares regression. Boundaries between headlands and bays (filled circles) are located by differentiating the shoreline model to identify changes in curvature (inflection points) between headland and embayed sections of beach. Smaller scale changes in curvature (open circles) may be omitted through visual interpretation. Example shown from Malaekahana and Laie bays, north-east Oahu.

high uncertainties typical of historical shoreline change rates.

Once headland and embayed beaches are identified, a comparison between shoreline change trends is conducted for the different geomorphic segments. Mean and median shoreline change rates, as well as the percentage of beach with an erosion or accretion trend are calculated. A mean rate for a section of beach (for example, a headland or embayment) is the average of all shoreline change rates from transects within that section.

The uncertainty of an average rate is calculated following Hapke *et al.* (2010) and Bayley & Hammersley (1946) (also described and utilized in Romine *et al.*, 2013) using an effective number of independent uncertainty observations (n^*) calculated from a spatially lagged autocorrelation of the rate uncertainties at individual transects along the shore. Uncertainties with individual and average shoreline change rates are reported at the 80% CI. A shoreline change rate is considered statistically significant if the absolute value of the rate is greater than the uncertainty.

Inspection of shoreline change rates along north-east Oahu suggests reduced erosion along sections of beach fronting sand-filled channels cut into the fringing reef. Locations of sand deposits along north-east Oahu are adapted from

Conger *et al.* (2009) and, where sand field data are not available, through visual identification using aerial photographs and LiDAR digital bathymetric models. Transects fronting the landward 'head' of sand-filled channels are visually identified to allow comparison of shoreline trends with beaches fronting shallow reef.

Spatial patterns of shoreline change along north-east Oahu are also identified that indicate longshore transport and deposition of sediment. Transects at headland and embayed beaches are divided into north and south subsections. The boundary between a north and south subsection is roughly the mid-point between the embayment (or headland) end boundaries. Similar to the statistical comparison of shoreline change within bays and headlands, average and median shoreline change rates were calculated, as well as percentage of transects that eroded or accreted, within the north or south subsections. The goal of this analysis is to identify patterns of change related to specific geomorphic regimes.

RESULTS

Patterns of historical shoreline change over the past *ca* 80 years (1927 to 2006) are analysed along roughly 14 km of beach along north-east Oahu from Malaekahana Bay through to Makalii

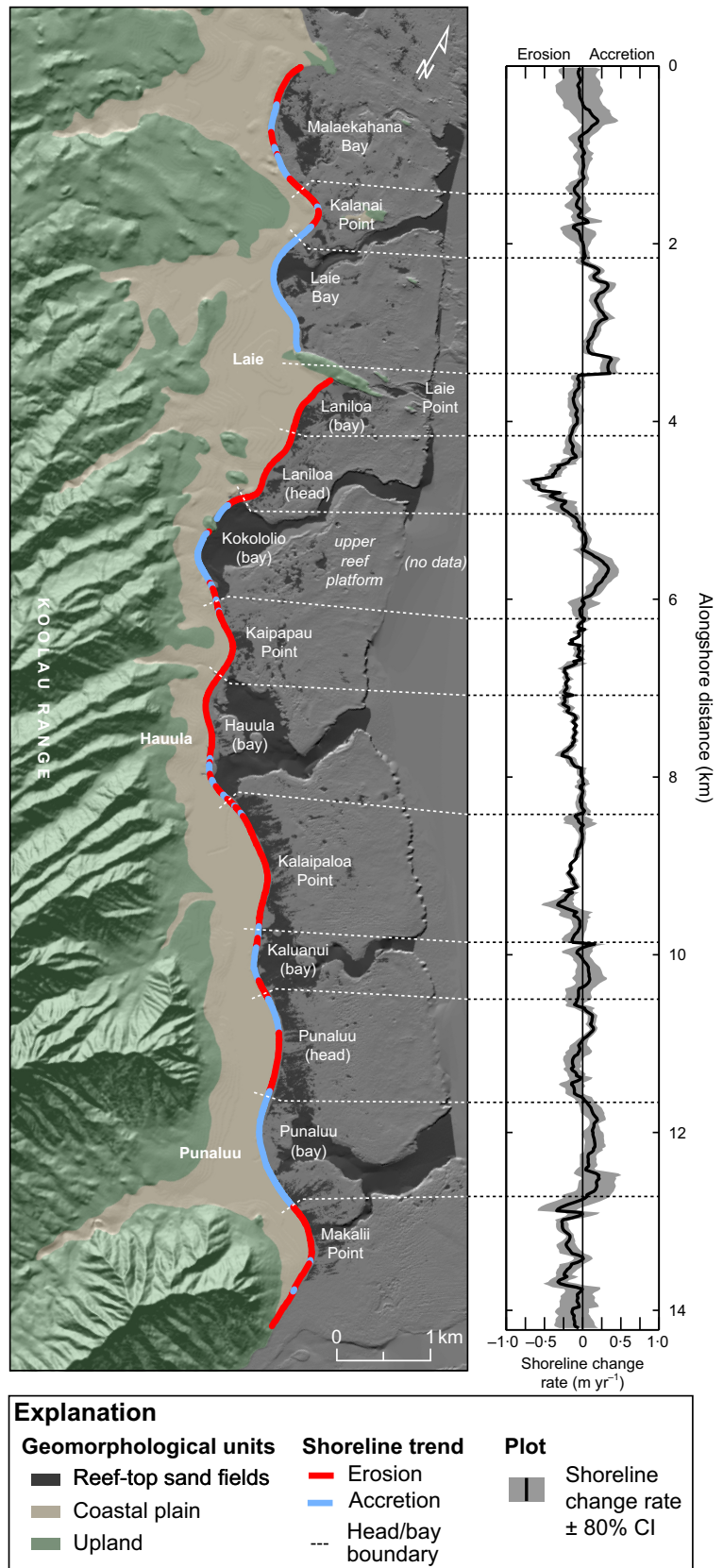


Fig. 5. Shoreline change trends for the beaches of Malaekahana through to Makalii Point, north-east Oahu, Hawaii (see Fig. 1 for location). Historical shoreline trends (plot, colour-coded alongshore bars) indicate greater erosion along headland sections of beach than along embayed sections. The surficial geology of the low-lying coastal plain (tan) is primarily unconsolidated Holocene carbonate beach and dune deposits and alluvium (Sherrod *et al.*, 2007). Locations of reef-top sand deposits were digitized by Conger *et al.* (2009) using visual interpretation of aerial photographs and bathymetric models.

Point (Fig. 5). Six segments (6.5 km in total) of shoreline are identified as headland beaches and seven segments (7.7 km in total) of shoreline are identified as embayed beaches. Of particular note, the shoreline at Laniloa has characteristics of both a headland and embayed beach and may be classified as a partially embayed headland. This study identifies Laniloa as a headland beach, to be consistent with the spatial scale of other headlands identified in the study area and because earlier historical shorelines at this location exhibited stronger headland-like morphology.

Overall, beaches within the study area exhibited a slightly erosional trend over the past century with an average rate of $-0.03 \pm 0.03 \text{ m yr}^{-1}$ (median rate -0.03 m yr^{-1}) and 65% of beaches indicating a trend of erosion, although only 29% of these are significant at the 80% CI (Table 1). Approximately 2.7 km of the study beaches were completely lost to erosion in the past century – nearly all of it (98%) fronting coastal armouring (for example, seawalls).

Over the past century sections of headland beach in the study area were significantly more erosional than embayed beaches (80% CI). Headland beaches eroded at an average rate of $-0.12 \pm 0.03 \text{ m yr}^{-1}$ (median rate -0.11 m yr^{-1}) while embayed beaches were slightly accretional overall, with an average rate of $0.04 \pm 0.03 \text{ m yr}^{-1}$ (median rate 0.01 m yr^{-1}). The majority (88%) of transects along headland beaches had a trend of erosion, whereas the majority (56%) of transects along embayed beaches had a trend of accretion. Of the eroding transects, 63% were located along headlands and 37% were located within embayments. Of accreting transects, 85% were located within embayments and 15% were located along headlands.

Table 1. Shoreline change trends for embayed beaches, headland beaches and all beaches within the study area of north-east Oahu, Hawaii (Malaekahana through to Makalii Point).

	Shoreline change rates (m yr^{-1})		Proportion of beach eroding and accreting [% (% significant at CI 80)]	
	Mean \pm CI 80	Median	Eroding	Accreting
Heads	-0.12 ± 0.03	-0.11	88 (45)	12 (4)
Bays	0.04 ± 0.03	0.01	44 (16)	56 (26)
ALL	-0.03 ± 0.03	-0.04	65 (29)	35 (16)

CI 80, 80% confidence interval.

Areas of stable and accreting beach are largely aligned with sand-filled channels fronting most of the embayments. Major sand-filled channels are found at Laie Bay, Kokololio, Hauula, Kaluanui and Punaluu (see Fig. 5 for locations). Shoreline trends for transects located directly landward of major sand-filled channels were slightly accretional overall, with an average rate of $0.04 \pm 0.03 \text{ m yr}^{-1}$ (median rate 0.02 m yr^{-1}) and 57% of transects indicating a trend of accretion (Table 2). Transects fronting shallow reef on both headland and embayed sections of beach, were more erosional overall, with an average rate of $-0.05 \pm 0.03 \text{ m yr}^{-1}$ (median rate -0.05 m yr^{-1}) and the majority (71%) had a trend of erosion.

The shoreline between Laniloa and Makalii Point exhibits significantly higher erosion on the southern half of the headland beaches (average rate $-0.17 \pm 0.05 \text{ m yr}^{-1}$, median rate -0.13 m yr^{-1}) compared with the northern half

Table 2. Comparison of shoreline change trends for beaches fronting shallow reef and sand-filled channels.

	Shoreline change rates (m yr^{-1})		Proportion of beach eroding and accreting [% (% significant at CI80)]	
	Mean \pm CI 80	Median	Eroding	Accreting
Reef	-0.05 ± 0.03	-0.05	71 (33)	29 (13)
Channel	0.04 ± 0.03	0.02	43 (16)	57 (26)

CI 80, 80% confidence interval.

Table 3. Comparison of shoreline change trends for north and south portions of headland and embayed beaches from Laniloa to Makalii Point (see Fig. 4 for location).

Region	Shoreline change rates (m yr^{-1})		Proportion of beach eroding and accreting [% (% significant at CI 95)]	
	Mean \pm CI 80	Median	Eroding	Accreting
<i>Laniloa – Makalii Point</i>				
Heads				
North	-0.09 ± 0.02	-0.07	84 (48)	16 (9)
South	-0.17 ± 0.05	-0.13	98 (53)	2 (0)
Bays				
North	-0.01 ± 0.03	-0.04	56 (36)	44 (21)
South	0.03 ± 0.05	0.00	48 (12)	52 (13)

CI 80, 80% confidence interval.

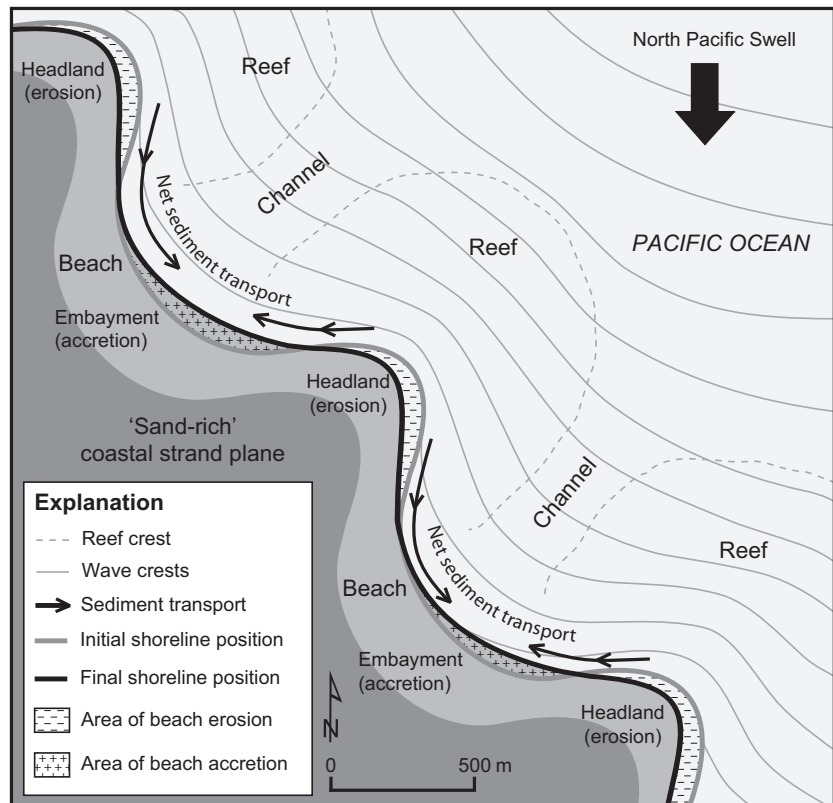


Fig. 6. Conceptual diagram of erosion and accretion trends and inferred net sediment transport between Laniloa Beach and Makalii Point (see: Fig. 5 for location).

of headlands (average rate $-0.09 \pm 0.02 \text{ m yr}^{-1}$, median rate -0.07 m yr^{-1}) (Table 3). This trend was not evident between Malaekahana and Laie bays. The shoreline between Laniloa and Makalii Point also exhibits more beach stability in the southern half of the embayments (average rate $0.03 \pm 0.05 \text{ m yr}^{-1}$, median rate 0.00 m yr^{-1}) compared with the northern half of the embayments (average rate $-0.01 \pm 0.03 \text{ m yr}^{-1}$, median rate -0.04 m yr^{-1}), although average rates are not significantly different at the 80% CI. This asymmetrical distribution of erosion and accretion trends along beaches in this section of the study area suggests predominant southerly transport of sediment – with sediment eroded at greater rates from the south side of headlands and deposited towards the southern end of bays (Fig. 6).

DISCUSSION

Overall, shoreline recession is expected with sea-level rise. However, the observed pattern of ‘preferential’ headland beach erosion highlights the importance of localized sediment processes in beach response to sea-level rise. Headland beaches that were generally characterized by

accretion (progradation) during falling sea-level after the Kapapa highstand have subsequently shifted to a pattern of erosion with modern sea-level rise, while embayed sections of beach have remained relatively stable or accreted.

These results indicate that efforts to forecast future shoreline change in similar coastal settings must account for spatial variations in shoreline change rates due to localized geomorphology and longshore sediment processes. The observations herein of historical shoreline change patterns run counter to predictions that would be expected from ‘bathtub style’ digital topographic flooding models and semi-empirical models of beach profile change (for example, the ‘Bruun Rule’; Bruun, 1954). These types of models would tend to predict relatively uniform shoreline recession with sea-level rise, given similar coastal elevation and slope. Attempting to predict shoreline change with sea-level rise using a bathtub style model or the Bruun Rule along north-east Oahu without consideration of sediment sharing within a littoral cell would fail to anticipate increased exposure to erosion at headland beaches and accretion within embayed sections of beach (35% of beaches) in this study. Recent work by Anderson *et al.* (2015) accounts for localized sediment processes in predicting

future shorelines with sea-level rise through a hybrid 'Bruun-type' model that incorporates historical shoreline erosion rates.

Although modern sea-level rise may be an important factor in headland beach erosion, beach response depends highly on sediment availability. Maximum wave energy in the study area occurs in winter when large refracted North Pacific swells impact reefs and beaches at oblique angles. Vitousek & Fletcher (2008) found that maximum annually recurring wave heights in Hawaii occur with winter swells from a north-west to north-east direction (from 300° to 360° and 0° to 60°) and wave-generated currents are the primary drivers of sediment transport (Norcross *et al.*, 2003). The pattern of asymmetrical headland beach erosion and embayment accretion – with increased erosion on the southern side of headlands and increased accretion on the southern side of embayments – suggests that northerly winter swell is primarily responsible for net southerly sediment transport.

The present data show that beaches fronting sand-filled palaeo-channels in the nearshore reef are substantially more stable than beaches fronting shallow reef flats or smaller sand deposits, which had an overall trend of erosion. Two possible drivers may be responsible for this: (i) there is net landward transport of sediment in the channels, nourishing the beaches; or (ii) sediment is being deposited at the landward end of the channels by converging longshore currents or swash zone processes transporting eroded sand from the headlands. An investigation of sediment movement in the Kailua channel at south-east Oahu by Cacchione *et al.* (1999) found that sedimentary bedforms (for example, ripples and sand waves) in the channel migrate landward under typical trade wind conditions supporting the first explanation. However, seismic profiles of channel-fill sediments (Grossman *et al.*, 2006) suggest variable sediment transport. The results of the present study suggest the explanation (ii) above.

Further investigation is needed to determine whether channels in the nearshore reef are typically a net source or sink for beach sands in Hawaii and elsewhere. In addition, future research on strand plain evolution through the late Holocene could include numerical modelling to provide additional information about hydrodynamic processes and help to quantify the relationships between wave conditions, sea-level rise and sediment transport.

CONCLUSIONS

Several lines of geological evidence indicate that beaches and coastal strand plains along the north-east Oahu coast are progradational features that formed with falling sea-level after a late-Holocene sea-level highstand *ca* 3500 yr BP. Strand plain deposits of similar age are common throughout tropical oceans along tectonically stable coasts. Headland beaches in the study area herein are characterized by higher rates of erosion compared to adjacent embayed beaches, which are stable or accreting. The observed spatial pattern of 'preferential' headland beach erosion suggests an overall shift from accretion to erosion particular to the headlands with the initiation of modern sea-level rise. Embayed beaches fronting channels in the nearshore reef are showing surprising resilience to sea-level rise because the beaches are maintained through sediment pathways between the eroding headlands and/or nearshore sand bodies. This pattern of headland erosion and bay infilling is a fundamental coastal process but is not well-documented on carbonate reef-fringed coasts prior to this study.

The results of this study show that beach response to sea-level rise in similar reef-fringed carbonate settings will depend strongly on localized coastal geomorphology, nearshore wave processes and sediment transport. As a result, some portions of beach may be expected to accrete under sea-level rise as eroded sediment is transported alongshore from adjacent sections of beach undergoing relatively high rates of erosion. Thus, even under conditions of sea-level rise, beach response will depend on sediment availability. In addition, asymmetrical patterns of erosion and accretion along headland and embayed beaches are inferred to result from predominant wave climate and resulting net longshore sediment transport.

These observations of historical shoreline change have important implications for coastal management and planning for sea-level rise for beaches on reef-fringed tropical coasts. Methods used to forecast shoreline change with sea-level rise, such as beach profile equilibrium models and digital models of coastal inundation, tend to predict fairly uniform shoreline retreat given similar topography along the shore. The results of this study show that differential erosion of certain coastal geomorphic features (for example, headland beaches) and sediment transport within a littoral cell must be accounted for when attempting to forecast shoreline change with sea-level rise.

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