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Observations of surface cobbles at two southern California beaches

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ABSTRACT

Southern California beaches are often sandy, but with largely undocumented cobble patches and berms. We describe the first multi-year, spatially extensive observations of surface cobbles at southern California beaches. The variation (spatial and temporal) of surface cobble distribution and backshore (e.g. upper foreshore) cobble morphology (slope, vertical extent, and elevation) are characterized using 11 years (2008–2018) of observations spanning 4.8 km of shoreline at Cardiff and Torrey Pines State beaches. Quarterly Global Positioning System surveys of beach elevation and visually identified sediment type (either sand or cobble) are used to create 1076 cross-shore profiles. Cobbles were not exposed continuously at either of these predominantly sandy beaches. The 202 cross-shore profiles with backshore cobbles and sandy foreshores are used for morphology analysis. Consistent with previous studies, cobble and sandy morphologies varied seasonally, and cobbles were most exposed during winter when wave energy increased. Extensive (vertical extent ≥ 2 m) backshore cobbles were usually fronted by low elevation, low slope sandy foreshores. At Torrey Pines cobble patches were occasionally exposed mid-profile on primarily sandy summer beaches. Persistent (2008–2015) backshore cobbles at Cardiff were apparently buried in 2016 by effects of a 2012 sand nourishment. Formation of year-round cobble piles on these seasonally sandy beaches may result from chronically reduced sand input owing to anthropogenic controls on river flooding and coastal cliff erosion (e.g. dams and seawalls).

1. Introduction

Cobbles occur on beaches worldwide (e.g. Holland & Elmore, 2008; Jennings & Shulmeister, 2002; Kirk, 1980), influence beach shape and morphology (e.g. Carter & Orford, 1984; Carter & Orford, 1993; Forbes et al., 1995), and may help stabilize shorelines (e.g. Allan & Komar, 2004; Carter & Orford, 1984; Forbes et al., 1995; Orford et al., 2002). Cobbles are relatively large-grained gravel. The three main types of gravel beach are pure gravel, mixed sand-gravel, and composite beaches (Jennings & Shulmeister, 2002). Composite cobble beaches generally consist of quasi-permanent cobbles on the backshore (or upper foreshore, hereinafter referred as backshore) and a sandy lower foreshore. We describe two sand-cobble beaches, with largely transient backshore cobble berms and isolated beach face cobble patches.

Similar to finer sediments, cobble transport depends on waves and morphology. However, cobble and sand transport dynamics are much different (e.g. Mason & Coates, 2001). For example, while sand is usually eroded from beaches by storm waves, cobbles may move onshore, forming large berms (e.g. Everts et al., 2002; Kuhn & Shepard, 1984). Cobble transport is understood poorly (e.g. Buscombe & Masselink, 2006), and spatially extensive observations are lacking (Komar, 2007). Along- and cross-shore transport of tracked cobbles have been reported (e.g. Allan et al., 2006; Curtiss et al., 2009; Dickson et al., 2012; Grottoli et al., 2015; Osborne, 2005; Stark & Hay, 2016). Schupp (Schupp, 1953) observed both on- and offshore cobble transport during cobble cusp formation over a few hours.

Composite sand-cobble beaches are of interest because of their potential resistance to shoreline erosion. Everts et al. (2002) found significant both upward and seaward cobble berm accretion of southern California composite beaches during the 1982–83 El-Niño winter, and suggest net-zero alongshore cobble transport. An artificial cobble berm face fronted by a sandy foreshore was partially buried by summer accretion on the foreshore, and exposed by winter erosion of the foreshore (Allan & Hart, 2007). These studies documented individual cobble movements and the evolution of a backshore cobble berm, but are usually qualitative or limited to sparse quantitative observations (e.g. Kuhn & Shepard, 1984).

Here, we describe 11 years of quarterly observations along cross-shore transects at two southern California beaches (spanning a total of 4.8 km) composed of cobbles and sand. Spatial and temporal variations of surface cobble and sand locations are identified, and related to wave conditions (seasonal and El Niño). Backshore cobble and sandy

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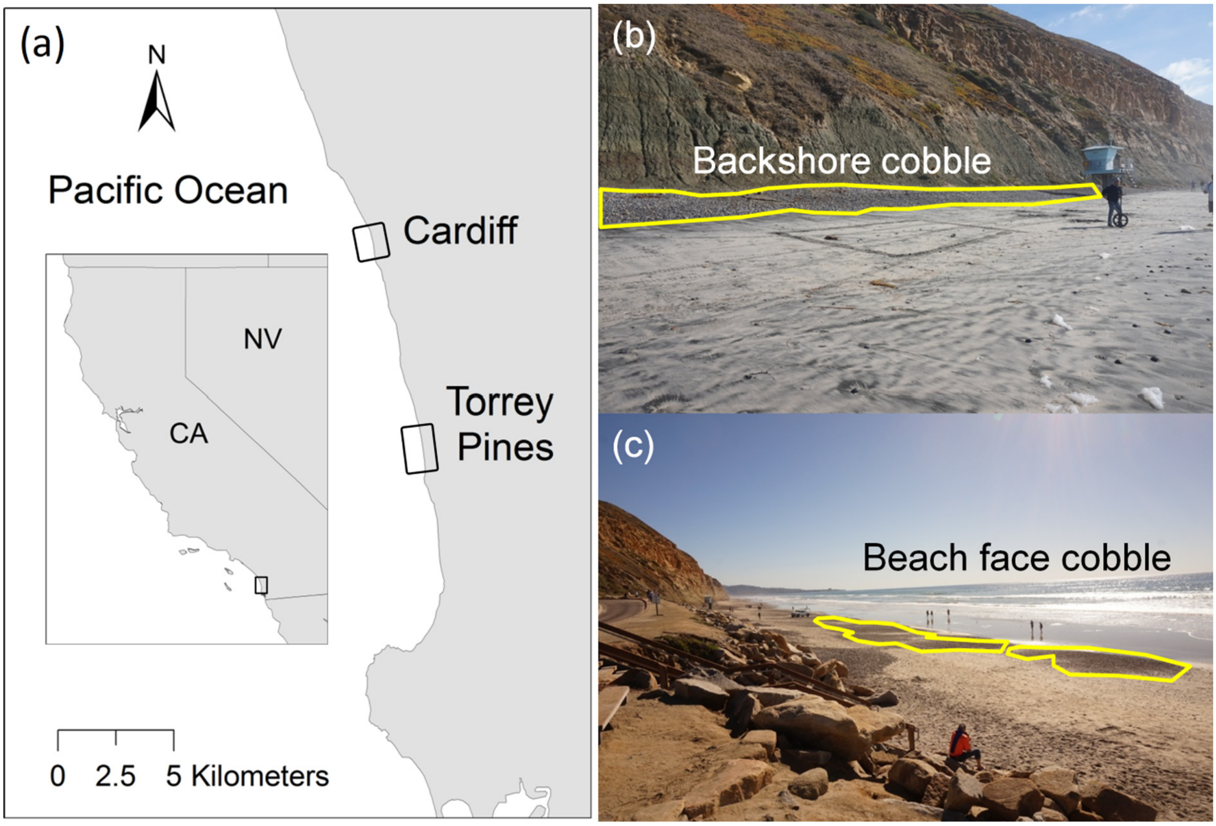

Fig. 1. (a) Study beach locations in southern California, and photos of (b) backshore and (c) beach face cobbles at Torrey Pines.

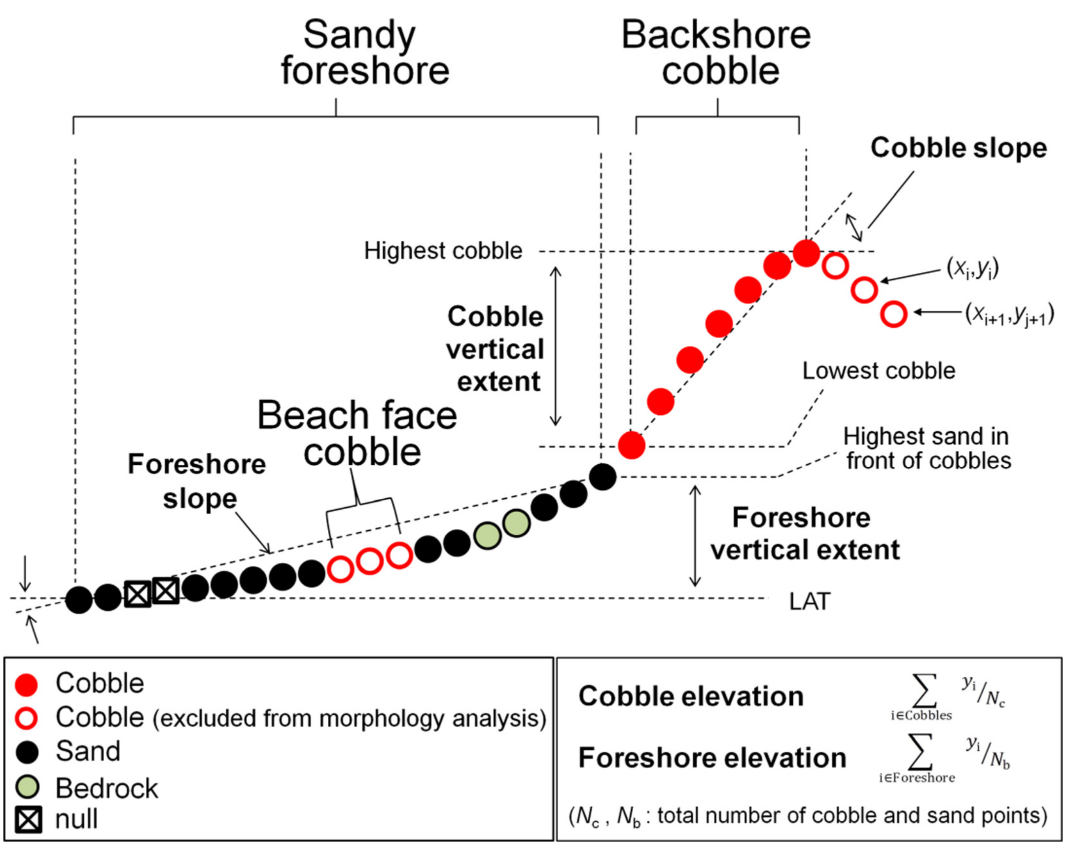

Fig. 2. Definition of backshore cobble and sandy foreshore morphologies. Cobbles on the beach face and landward of the highest cobble (unfilled red circles) are excluded from morphology analysis, but included in spatio-temporal distribution analysis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

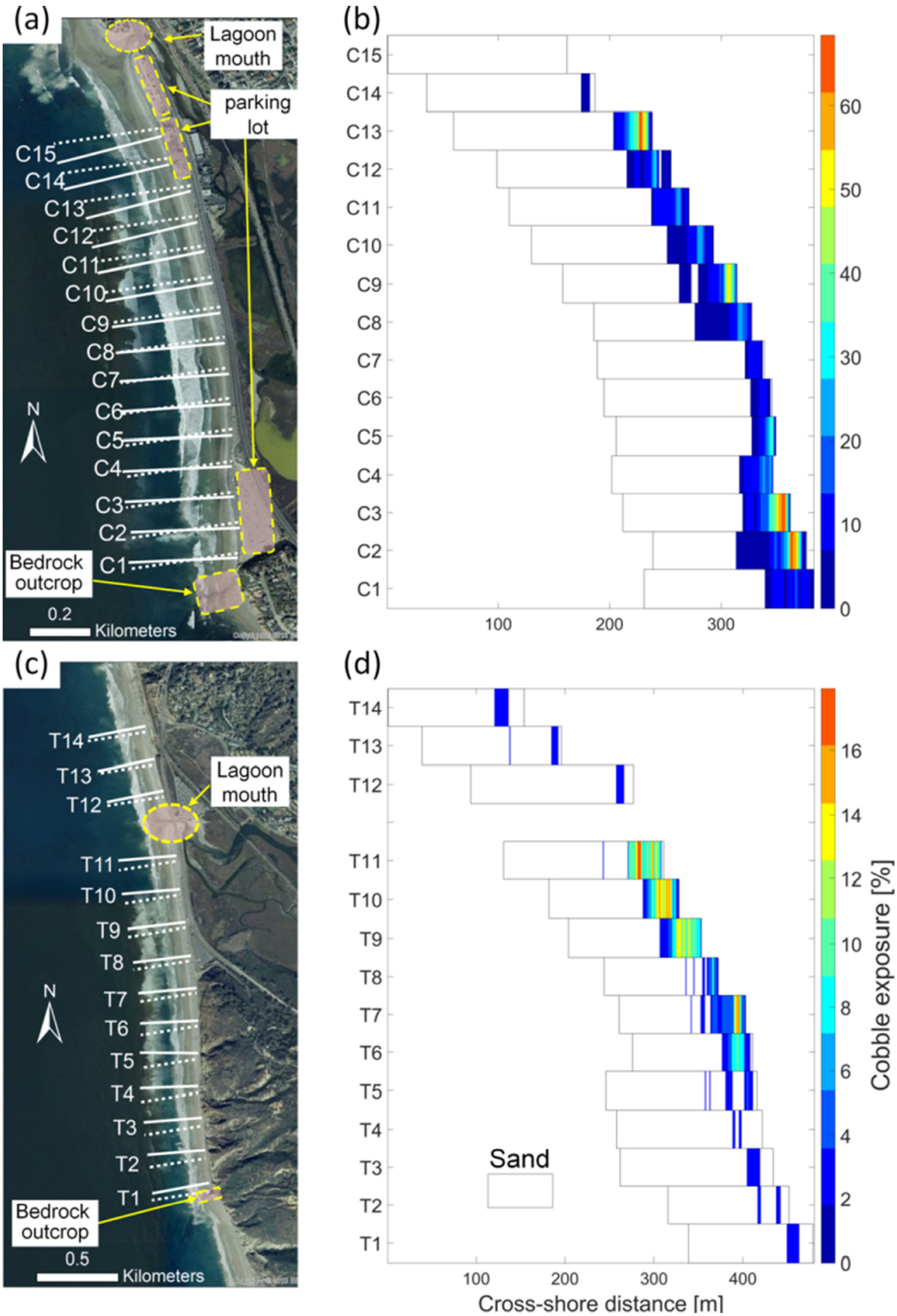

Fig. 3. Spatial distribution of transects and cobbles at (a, b) Cardiff and (c, d) Torrey Pines. (a, c) Solid (dashed) lines are transects before (after) coordinates changed (January 2012 at Cardiff and July 2016 at Torrey Pines). (b, d) Cobble exposure (time-average percent) between 2008 and 2018 versus cross-shore and alongshore location. Transect alongshore spacings are 100 m (Cardiff) and 200 m (Torrey Pines). Data bins are 1-m cross-shore. Distance and percentage color scales differ between sites.(For interpretation of the references to color in this figure legend, the reader is referred to the online version of this chapter.)

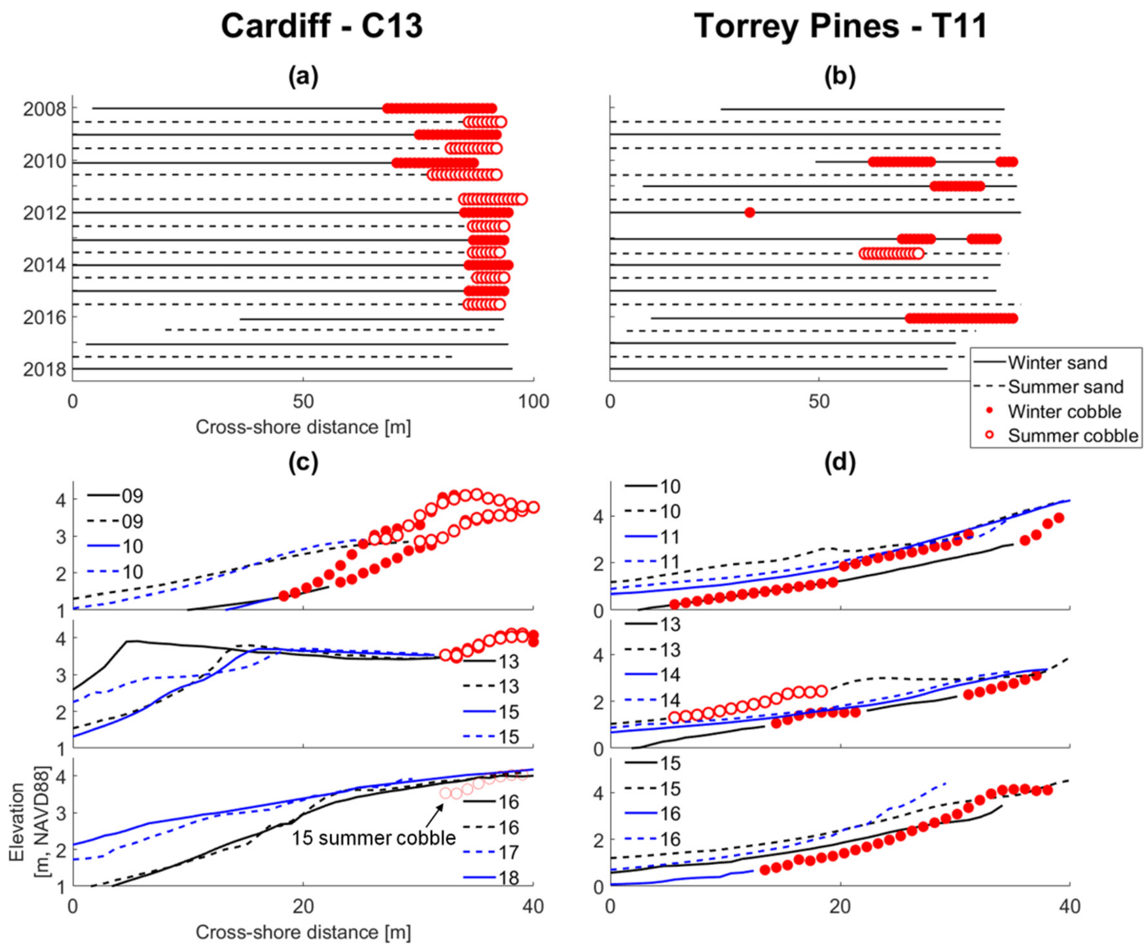

Fig. 4. Winter (Dec–Feb) and summer (Jun–Aug) locations of cobble and sand (see legend) versus time and cross-shore distance at transects (a) C13 Cardiff and (b) T11 Torrey Pines. Elevation versus cross-shore distance for selected profiles between (c) 2009 and 2018 along C13, and between (d) 2010 and 2016 along T11. In 2016–2018 at Cardiff in 4c, sand was present at elevations above previously exposed cobbles. C13 and T11 have relatively high cobble exposure (Fig. 3).

foreshore morphologies (slope, vertical extent, and elevation) are characterized, and compared with previous observations.

2. Study site

Two southern California beaches, Cardiff (1.8 km) and Torrey Pines (3.0 km), separated by ~7 km (Fig. 1) were studied. The beaches are composed of sand and cobbles that are usually not intermixed, and can be considered composite beaches (Jennings & Shulmeister, 2002). Spring tidal range is ~2 m. The study sites are exposed to waves generated by local winds and distant storms in both hemispheres. During winter, swell from the North Pacific and Gulf of Alaska is most energetic, whereas less energetic swell from the South Pacific dominates in summer. Both beaches exhibit seasonal sand level changes with summer accretion and winter erosion (Ludka et al., 2015). The typical sand size is D_{50} = 0.16 mm (median) at Cardiff and 0.23 mm at Torrey Pines (Ludka et al., 2015; Ludka et al., 2016) with considerable alongshore variation (see Fig. 6, Yates et al., 2009). In November 2012, ~68,000 m^3 of offshore sand (D_{50} = 0.57 mm, coarser than native) was placed on the subaerial portions of Cardiff, whereas Torrey Pines was last nourished in 2001 (Ludka et al., 2015; Ludka et al., 2016).

The study beaches are located in the Oceanside littoral cell (Inman & Frautschy, 1966) where sediment generally drifts southerly (Flick, 1994). The development of the region have altered the coastline (Flick, 1993; Griggs et al., 2005; Inman, 1976; Young et al., 2010), including a reduction in natural beach sediment supply caused by river damming (Willis & Griggs, 2003), coastal armoring (Runyan & Griggs, 2003; Young & Ashford, 2006), and urbanization (Warrick & Rubin, 2007; Young et al., 2010). The deficit in natural beach sediment supply in the Oceanside littoral cell has been counteracted by numerous beach replenishment projects since the 1940s with > 15 million m^3 of sand (Flick, 2005).

Cardiff and the northern section of Torrey Pines are backed by a low lying lagoon spit developed with a coastal highway, infrastructure, and parking lots usually protected by rip rap. Both lagoon mouths are engineered, spatially fixed, and intermittently connected to the ocean. The southern half of Torrey Pines is backed by 50–60 m high coastal cliffs. Rip rap, coastal cliffs, and parking lots fix the backshore position at both sites except for lagoon mouths. Both sites have an elevated bedrock outcrop at their southern end.

Previous studies (e.g. Kuhn & Shepard, 1984; Matsumoto & Young, 2018) documented cobbles at both beaches (Fig. 1b and c), although little is known about cobble amounts in the Oceanside littoral cell and cobble transport. Matsumoto and Young et al. (2018) mapped surface cobbles using ground-based mobile LiDAR data, and estimated upper beach surface cobble coverage during October 2017 and March 2018. Cobbles at the study sites have been transported by waves onto adjacent structures, parking lots, and highways, damaging infrastructure (Kuhn & Shepard, 1984; Young et al., 2018).

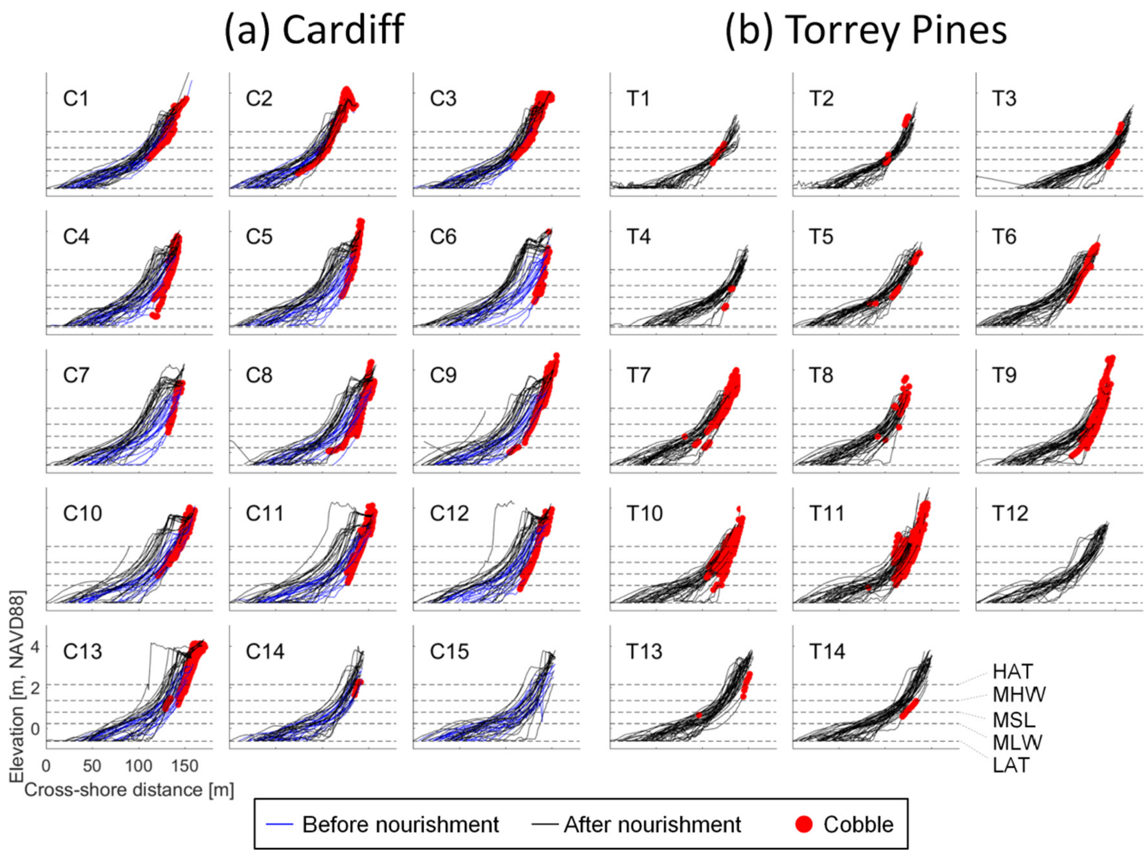

Fig. 5. Elevation versus cross-shore distance for each transect at (a) Cardiff and (b) Torrey Pines. Blue (black) lines in panel (a) show profiles before (after) the 2012 sand nourishment. HAT, MSL, and MLW denote the highest astronomical tide, mean sea level, and mean low water elevations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Methods

3.1. Cross-shore profiles

Elevations were surveyed quarterly between January 2008 and July 2018 on cross-shore transects from the back beach to about 8 m water depth, spaced 100 m alongshore at Cardiff (15 transects), and 200 m at Torrey Pines (14 transects). Subaerial and submarine portions of the transects were surveyed with Global Positioning System (GPS) equipped all-terrain vehicle (ATV), and dolly or Jet Ski, respectively, with 10 cm vertical accuracy. The big-wheeled dolly, weighted to maintain contact with the seabed and with an elevated mast supporting the GPS receiver, is manually pushed into the surf zone. On the ATV only, sediment type (either sand, cobble, or bedrock) was visually classified and logged with a 3-way recording switch. Cross-shore profiles with elevations above the lowest astronomical tide (LAT, −0.64 m NAVD88) were constructed using the mean of data in bins that are 1-m cross-shore, and 20-m alongshore (centered on the cross-shore transect). Alongshore deviations from transect lines occurred during the GPS surveys owing to factors such as waves, currents, and steep topography (e.g. scarps). “Null” was assigned at locations without GPS data point in the 1×20 m^2 search area. Profiles with more than half “null” points were excluded. Profiles with the highest elevation lower than mean high water (MHW, 1.56 m NAVD88) elevation were also excluded because of possible incomplete surveys. In total, 1076 cross-shore profiles were retained and analyzed.

A single sediment type was assigned to each 1 m-spaced cross-shore profile point. Bedrock was assigned when there was at least one bedrock data point within the 1×20 m^2 search area, whereas cobble was assigned when at least one cobble point but no bedrock data point existed. Sand was assigned in other cases. Overall, 2.8% and 0.1% of the total points were classified as a cobble and bedrock, respectively.

3.2. Cobble and sand distribution and morphology

The analysis includes estimations of (i) cobble exposure: at a given location, the number of surveys with cobbles observed divided by the number of total surveys (e.g. cobbles or sands were observed) and (ii) cobble coverage; for each survey, the cobble area divided by the total beach area, cobble plus sand. The backshore cobble morphology analysis ignored beach face cobbles and cobbles landward of the most elevated cobbles (unfilled red circles, Fig. 2). Morphology analysis used the 202 composite (of the total 1076) profiles that included backshore cobbles and sandy foreshores.

3.3. Waves

A buoy-driven, regional wave model (O'Reilly et al., 2016) was used to estimate hourly wave conditions in 10 m water depth for each transect. The model includes the effects of complex offshore bathymetry and varying beach orientation on wave exposure. Four wave metrics were used to represent wave conditions: Hs, wave runup, energy flux, and total water level (TWL). TWL was the sum of the observed water level at the La Jolla tide gauge (station 9,410,230) and the vertical height of wave runup (Ruggiero et al., 2001; Shih et al., 1994), approximated as the level exceeded by 2% of wave uprushes ((Stockdon et al., 2006), equation (18)). Energy flux is wave energy multiplied by deep water group velocity which includes wave period. The effect of beach morphology on runup is not included. The number of TWL hours exceeding 2.5 m elevation (NAVD88) was used as a metric of elevated TWL (denoted as high TWL duration).

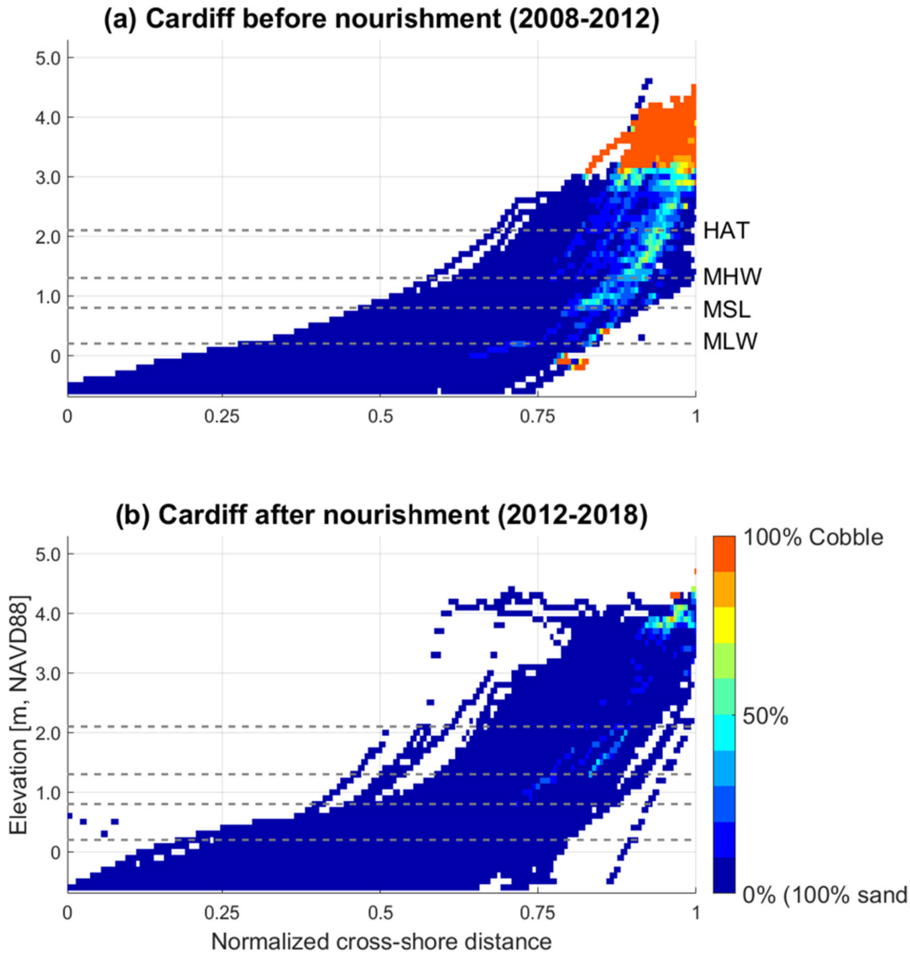

Fig. 6. Percent cobble and sand exposure (color bar) versus cross-shore distance and elevation for all Cardiff transects (a) before and (b) after the 2012 sand nourishment. Cross-shore distance is normalized by the widest cross-shore distance during each survey period (154 m and 177 m in panels a and b, respectively). (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this chapter.)

4. Results

4.1. Spatio-temporal cobble and sand distribution

4.1.1. Alongshore and cross-shore cobble exposure

Over the 11 year study period, cobbles were never exposed at most locations at both sites (white areas in Fig. 3b and d). Cobbles were most commonly exposed on the back beach, and more often exposed in Cardiff than Torrey Pines, with maximum (time-averaged) for a single profile location of 69% and 18% respectively (Fig. 3). No location at either beach had permanently (100%) exposed cobble.

Cobble exposure considerably varied alongshore (Fig. 3). At Cardiff cobbles were frequently exposed on the C2, C3, and C13 transects with exposure reaching > 50%, whereas cobbles were not observed on C15. At Torrey Pines cobbles mostly occurred in the central section (T9–T11) with cobble exposure > 10%. The highest exposure was immediately south of the lagoon mouth (T11) and decreased towards the south (Fig. 3d). Cobble coverage was lowest (< 4%) at the most southern (T1–T5) and northern (T12–T14) transects.

The temporal evolution of example transects C13 and T11 with relatively high cobble exposure (Fig. 3) illustrates contrasting cobble exposure behaviors between Cardiff and Torrey Pines (Fig. 4). At C13, backshore cobbles were exposed continuously for 8 years (from the first survey in 2008 to summer 2015, Fig. 4a), but not afterwards. Cobble exposure expanded seaward between 2009 and 2010 (Fig. 4c). From 2013 to 2015 the front face of the nourished sand eroded, but backshore cobbles remained stationary. From 2016 to 2018, the backshore was sandy and elevated above the previous cobbles, suggesting cobble burial by overwash of the eroding beach face. Cobbles on T11 were more seasonal, with the largest exposure during the 2015–16 El Niño winter (Fig. 4b). T11 had scattered beach face and backshore cobbles with location varying through time, including mid profile cobbles on primarily sandy summer beaches (Fig. 4d).

Cross-shore profiles for each transect further compare cobble and sand location patterns at Cardiff and Torrey Pines (Fig. 5). For example, at Cardiff the exposed surface cobble was more consistently located in space (cross-shore) than at Torrey Pines. At Torrey Pines, cobbles on transects with relatively high cobble exposure (e.g. T10 and T11, Fig. 5b) were more variable and spatially scattered than at Cardiff, with overlapping sand and cobble cross-shore location at higher elevations. The 2012 nourishment caused relatively large variations in the Cardiff sandy cross-shore profile (Fig. 5a).

Superimposed all cross-shore cobble and sand exposure at Cardiff (Fig. 6a) shows that most cobbles were located between mean sea level (MSL, 0.89 m NAVD88) elevation and 4.5 m (NAVD88). Prior to the 2012 sand nourishment, most observations above 3.3 m (NAVD88) were cobble, whereas elevations < 3 m were both cobble and sand. After nourishment, the zone of high cobble exposure considerably decreased, and sand occurred at higher elevations than pre-2012 nourishment (Fig. 6b).

4.1.2. Cobble coverage and waves

Monthly Hs, wave runup, energy flux, and high TWL duration were in the range of 0.6–1.5 m, 0.4–0.9 m, 4.0e+3–4.3e+4 $J{\cdot}m^{-1}s^{-1}$, and

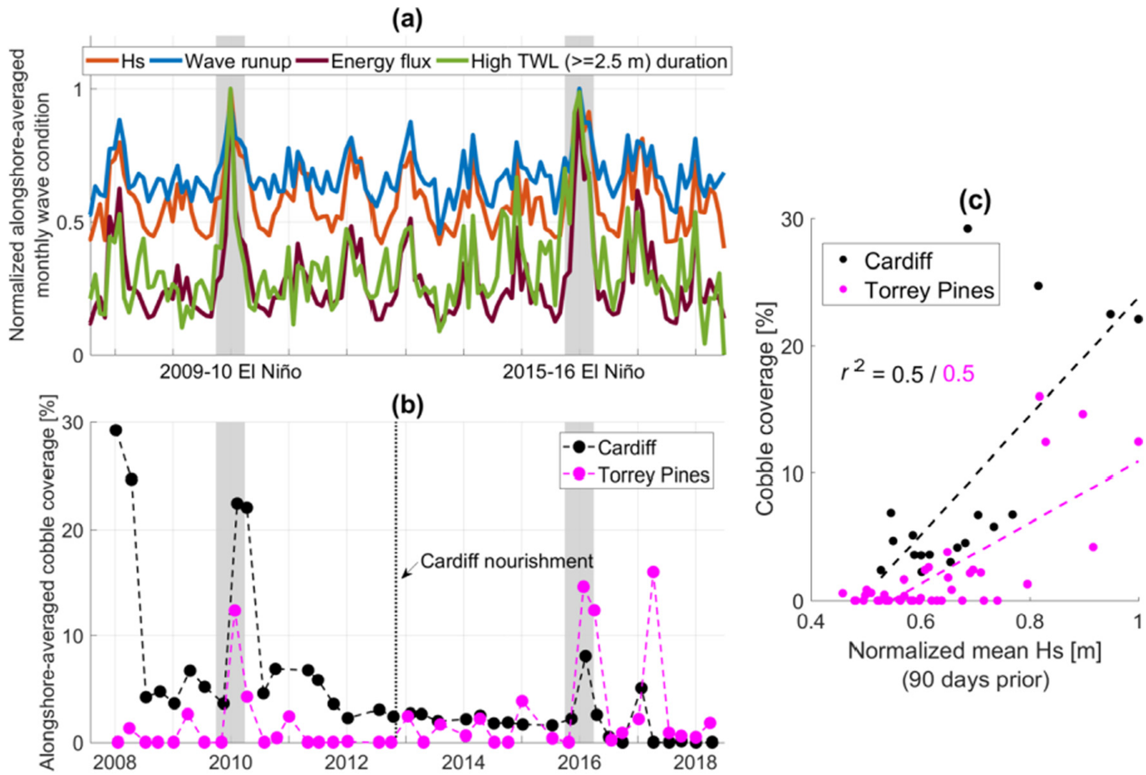

Fig. 7. Time series of (a) normalized alongshore-averaged monthly wave conditions, and (b) alongshore-average cobble coverage during 2008–18 at Cardiff (black) and Torrey Pines (magenta). Gray zones indicate 2009–10 and 2015–16 El Niños. Dotted line indicates the 2012 Cardiff sand nourishment. (c) Cobble coverage versus normalized mean Hs (90 days prior). Cardiff data after the 2012 sand nourishment is omitted. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

0–63 h, with means of 0.8 m, 0.6 m, 1.2e + 4 $J{\cdot}m^{-1}\,s^{-1}$, and 11 h, respectively. The largest Hs, wave runup, energy flux, and high TWL duration were in winter (Fig. 7a). Cobble coverage fluctuated between 0–29% at Cardifff, and 0–15% at Torrey Pines, with the largest cobble coverage observed in winter (Fig. 7b).

Maximum wave metrics (Hs, wave runup, energy flux, and high TWL duration) and cobble exposure were observed during the 2009–10 and 2015–16 El-Niño winters. At Torrey Pines, coverage was similar in both El Niños (~13–16%), and was also elevated in the following 2016–17 winter. At Cardiff, cobble coverage exceeded 20% in 2007–08 and 2009–10 El Niño winters. Exposure was notably low (1–3%) for several winters after the 2012 sand nourishment, and reached only 9% in 2015–16 El Niño winter (Fig. 7b). Neglecting the Cardiff nourishment, cobble coverage generally correlated with preceding (90-day prior) Hs (r^2 = 0.5, Fig. 7c), wave runnup (r^2 = 0.4–0.6), energy flux (0.5–0.6), and high TWL duration (0.3–0.6) at both sites.

4.2. Backshore cobble and sandy foreshore morphologies

The vertical cobble extent (defined in Fig. 2) at Cardiff and Torrey Pines ranged 0.2–2.5 m (25th and 75th percentiles, Fig. 8c), with maximum vertical extent in winter (Dec–Feb) and spring (Mar–May) (median values of 1.6–1.8 m at Cardiff and 0.9–1.1 m at Torrey Pines). During summer (Jun–Aug) and fall (Sep–Nov), the median vertical extent was smaller at 0.9 and 0.4–0.8 m at Cardiff and Torrey Pines, respectively. The backshore cobble mean elevation, usually above the highest astronomical tide (HAT, 2.2 m NADV88), was highest in summer and fall, likely because lower beach-face cobbles were buried by accreting sand (Fig. 4c and 8e). As expected, the largest vertical extent and highest mean elevation of sandy foreshores occurred in summer and fall (Fig. 8d and f), opposite of seasonal cobble vertical extent. Large variations of vertical extent and mean elevation of both backshore cobbles and sandy foreshores occurred during winter and spring (Fig. 8c–f). Neither backshore cobble nor sandy foreshore slope varied seasonally (Fig. 8a and b). Foreshore slopes (< 3°) were less than backshore cobble slopes (usually > 5°, median 8–10°).

Neglecting backshore cobbles with small vertical extent (< 2 m), the vertical extent of backshore cobbles was significantly inversely correlated with foreshore sandy slope, vertical extent, and mean elevation (r^2 = 0.6–0.7, Fig. 9d, e, and f). Note that the total vertical extent varies over time because the elevation of the highest cobbles varies (not shown). The strongest correlation was between backshore cobble mean elevation and sandy foreshore vertical extent (r^2 = 0.7–0.9, Fig. 9h). In contrast, the backshore cobble slope only weakly correlated with sandy foreshore slope (r^2 = 0.4, Fig. 9a). The morphological correlations indicate backshore cobbles with large vertical extent were usually fronted by low elevation, low gradient sandy foreshores.

5. Discussion

Cobbles were not permanently exposed at any sampled location, likely owing to sand availability, especially at the nourished Cardiff beach. Nonetheless, the present results are generally consistent with past observations of composite beaches with more abundant, near-permanent backshore cobbles. For example, exposed summer backshore cobbles spanned a relatively smaller vertical extent, with a more elevated mean, than in winter (Figs. 4c, 8c, and e), consistent with Allan and Hart (Allan & Hart, 2007) who observed summer burial of cobbles at lower beach elevations. Backshore cobbles expanded seaward at Cardiff during the 2009–10 El Niño winter (Fig. 4c), similar to the observed seaward and upward shift of cobble berms during the 1982–83 El Niño winter (Everts et al., 2002). The results also differ from previous observations. Cobble exposures in Torrey Pines varied throughout the cross-shore profile with time (Fig. 4b) including mid

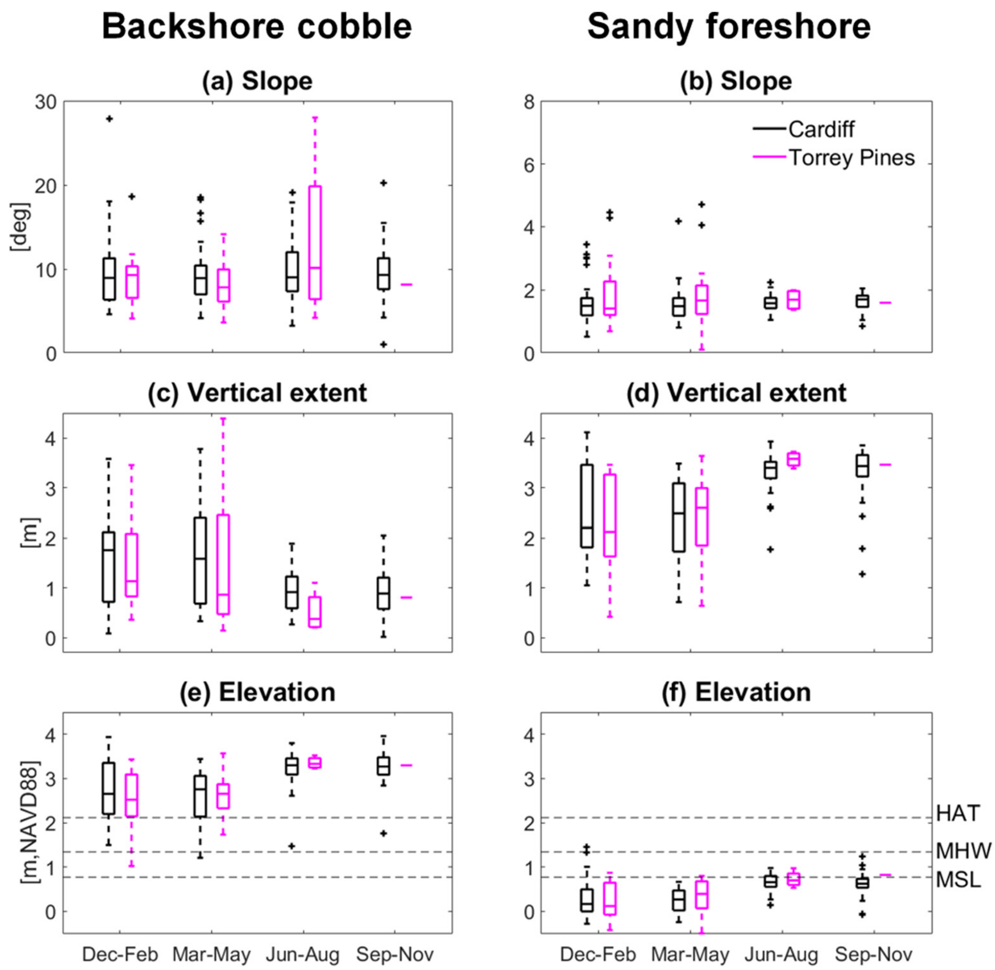

Fig. 8. Backshore cobble (left) and sandy foreshore (right) (a, b) slope, (c, d) vertical extent, and (e, f) elevation at Cardiff (black) and Torrey Pines (magenta) versus season. The central line of the box, and the bottom and top edges of the box correspond to the median, the 25th and 75th percentile, respectively. "+" markers indicate outliers. Cardiff data after the 2012 sand nourishment is omitted. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

profile cobbles on mostly sandy summer berms (e.g. 2013 summer profile, Fig. 4d). The cross-shore cobble and sand extent at higher elevations (e.g. MHW, HAT) overlapped (Fig. 5b) indicating active cross-shore cobble movement, rather than the presumably static cobbles at Cardiff and reported on other composite beaches (e.g. Allan & Hart, 2007).

The 2012 sand nourishment at Cardiff reduced cobble exposure, and coverage during the 2015–16 El Niño was about half the coverage during 2009–10 El Niño event (Fig. 7b). In contrast, at the unnourished (since 2001) Torrey Pines, cobble exposure was similarly elevated during both El Niños. On C13 transect, the front face of the nourished sands eroded between 2013 and 2015, and the most elevated backshore cobbles remained exposed (Fig. 4a and c). During 2016–2018, these remaining backshore cobbles were not observed. Ludka et al. (2016) observed the 2012 nourished sands at Cardiff remained subaerial for several years after placement, suggesting the eroding front face of the nourished sands retreated to the backshore and buried the previously exposed backshore cobbles.

Cobble exposure considerably varied alongshore (Fig. 3). At Torrey Pines, cobble exposure was highest immediately south of the lagoon mouth and decreased southward (Fig. 3c and d), with few cobbles north of the lagoon mouth. At Cardiff, cobble exposures were higher near two parking lots (Fig. 3a and b). The high cobble exposure locations do not suggest any obvious transport paths. To understand the alongshore variation of cobble exposure, investigations are needed of cobble sources, sinks, and transport (e.g. tracking individual cobbles, Allan et al., 2006).

Gravel beach morphology is influenced by sediment composition and ratios (e.g. Horn & Walton, 2007; Quick, 1991). Cobble movements and morphology of composite beaches may also vary depending on sediment composition ratios. Cobbles may increase resistance to shoreline change (e.g. Doria et al., 2016; Yates et al., 2009). Beaches composed of coarse sediment are generally more stable than finer grained beaches under wave attack (Bradbury & Powell, 1992; Carter & Orford, 1984; Forbes et al., 1995; Orford et al., 2002). Cobble beaches are therefore potentially attractive for 'natural' erosion defense schemes against coastal retreat. Composite beaches could provide the recreational value of a sandy foreshore and the stability of a cobble berm. Engineered cobble berms have been used for shoreline stabilization in Oregon (e.g. Allan & Komar, 2004), Surfers Point in Ventura (Kochnower et al., 2015), and recently in Carlsbad, California. The present study describes the basic shape, morphology, and temporal variability of sand-cobble profiles, using only surface cobble observations. The rates and patterns of cobble movement, cobble grain size and shapes, sand-cobble ratios and volumes, and the influence of cobbles on beach morphology are unknown.

Sand supplied to southern California beaches from rivers and coastal cliff erosion has decreased significantly over the last century, owing to flood control, seawalls, and urbanization (e.g. Slagel & Griggs, 2008; Young et al., 2010). Sand loss offshore under the influence of gravity, facilitated by submarine canyons and other conduits, continues unabated. Cobbles, possibly moving shoreward during storms when

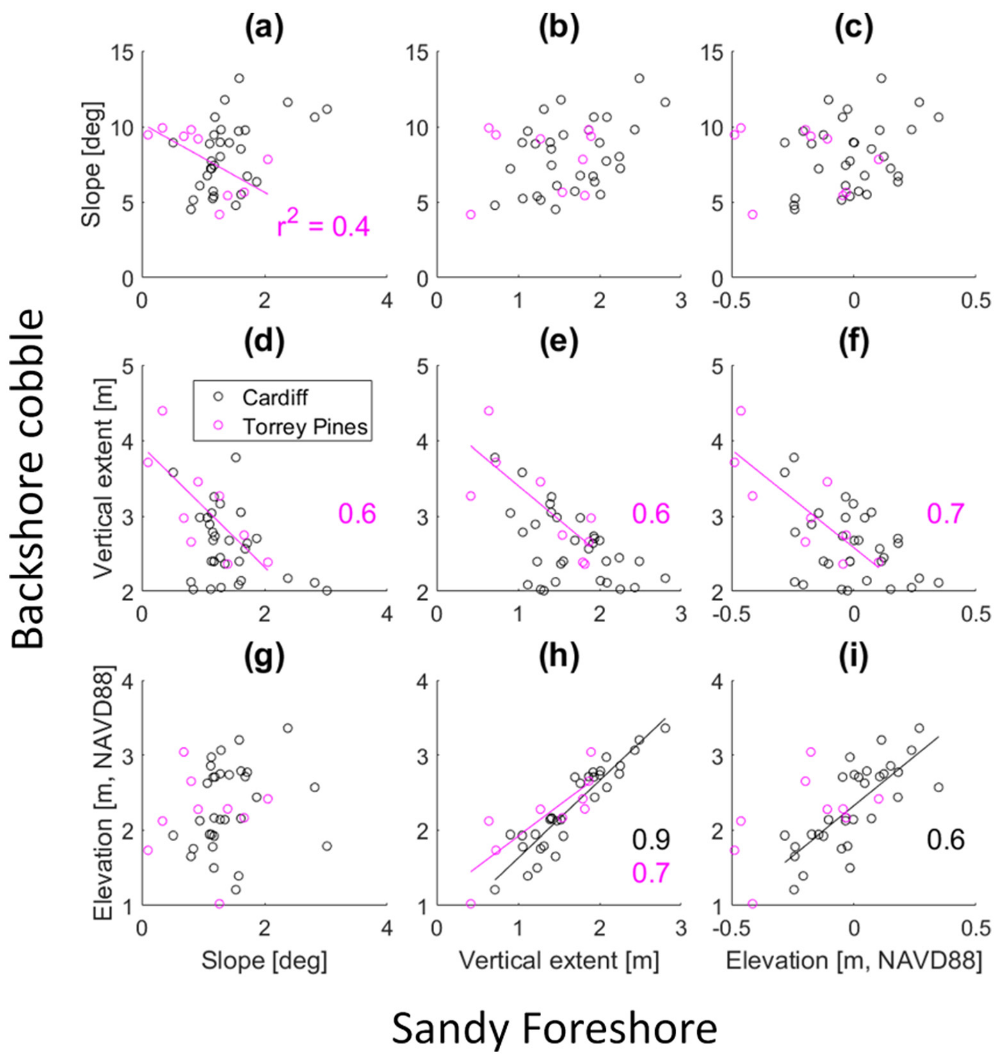

Fig. 9. Backshore cobble versus sandy foreshore morphology at Cardiff (black, n = 31) and Torrey Pines (magenta, n = 9): backshore cobble slope versus (a) sandy foreshore slope, (b) sandy foreshore vertical extent, and (c) sandy foreshore elevation: backshore cobble vertical extent versus (d) sandy foreshore slope, (e) sandy foreshore vertical extent, and (f) sandy foreshore elevation: and backshore cobble elevation versus (d) sandy foreshore slope, (e) sandy foreshore vertical extent, and (f) sandy foreshore elevation. Only backshore cobbles with vertical extent ≥ 2 m are shown. Linear trend lines and correlation (r^2) are shown for $r^2 \geq 0.4$. Cardiff data after the 2012 sand nourishment is omitted. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

exposed by decreasing sand levels, may replace lost smaller sand grains. We speculate that continued reduced sand input (owing to river flood and coastal cliff erosion control), coupled with sea level rise, may encourage formation of year-round backshore cobble berms on previously seasonal sandy beaches.

6. Conclusions

We describe surface cobbles using 11 years of quarterly observations at two southern California beaches. Cobbles were not continuously exposed, although at some locations cobbles persisted for several years. At both sites cobbles were more often observed on the back beach during winter when waves are most energetic, consistent with previous observations of composite beaches. In contrast, at some locations cobble exposure varied over the cross-shore profile including occasional mid profile cobbles on primarily sandy summer beaches.

Data availability

Datasets related to this article can be found at https://doi.org/10.6075/J0FB518T, hosted at UC San Diego Library Digital Collections (Matsumoto et al., 2019).

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