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Seaweed-assisted, benthic gravel transport by tidal currents

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ABSTRACT

Traction transport of pebbles and cobbles occurs subtidally at current velocities below 0.5 m s^{-1} when seaweed attached to clasts provides additional lift and drag to the clast. In the Juan de Fuca Strait, British Columbia, Canada, the seaweed *Cymanthere triplicata* commonly attaches to pebbles and provides sufficient additional surface area for tidal currents to drag the clast along the seafloor. Using in situ measurements of current velocities at 13 m water depth, the threshold for initiation of motion of a 30 mm pebble with attached seaweed is 0.3 m s^{-1}. This is approximately one order of magnitude less than the activation velocity for a 30 mm pebble without attached seaweed.

In addition to kelp-rafted (floated) gravel, seaweed-assisted, benthic gravel transport is possible in marine settings where unidirectional currents (e.g., tidal currents, storm-induced bottom currents) are sufficient to transport pebbles alongshore, and into and across the offshore (below fairweather wave base). If preserved in the rock record, deposits of algal-enhanced gravel deposited via unidirectional, subtidal currents will likely appear as isolated gravel clasts encased in sandstone, reflecting the similar current velocities required to transport these two clast groups.

1. Introduction

Seaweed-assisted gravel transport is a common phenomenon in high-latitude oceans and is intermittently used to explain the sporadic occurrence of pebbles and cobbles in finer-grained marine sediments. Descriptions of kelp-rafting (e.g., Emery and Tschudy, 1941; Menard, 1953; Shumway, 1953; Emery, 1960; Smith, 2002; Collins et al., 2010; Garden and Smith, 2011; Garden et al., 2011), and wave-driven, landward transport of gravel with attached seaweed (e.g., Shaler, 1895; Lang, 1926; Ben-Avraham, 1971; Kudrass, 1974; Woodborne et al., 1989; Smith and Bayliss-Smith, 1998) are common in the literature. However, few studies consider the dynamics of seaweed-assisted, benthic gravel transport (SABGT) by unidirectional currents, where the seaweed acts as a “sail” and drags clasts along the seafloor (Brown, 1911; Emery, 1960; Gilbert, 1984).

Recognition of seaweed-attached gravel transport by waves dates back over 130 years, when Kinaham (1879) speculated that attached kelp aided in the landward transport of large cobblestones (Ben-Avraham, 1971). Later, Dunn (1911) published illustrations of kelp-rafted cobbles from Australia and New Zealand, which was followed by a series of reports on kelp-rafted gravel from the continental shelf and the deep sea (Emery and Tschudy, 1941; Shumway, 1953; Emery, 1960, 1963; Gentle, 1987; Woodborne et al., 1989; Bennett et al., 1996). In general, it is hypothesized that seaweed and their gravel clast anchors are freed from the substrate under the influence of storm waves and are either carried shoreward by waves (Darling, 1947; Woodborne et al., 1989; Smith and Bayliss-Smith, 1998) or float seaward in circulating surface currents (Shumway, 1953; Smith, 2002; Garden et al., 2011). The mechanics of seafloor seaweed transport, however, is poorly documented.

In the Juan de Fuca Strait, Canada, SABGT was observed in a unidirectional flood-tide current in 13 m water depth. Clasts with seaweed attached were transported alongshore by tidal currents at velocities significantly below their expected entrainment velocity. Using measurements of current velocity from doppler meters deployed on the seafloor, it is possible to establish the current velocity under which the clasts are transported. These values are then used to quantify the activation velocity for gravel with attached seaweed. The potential for SABGT is then discussed.

1.1. Seaweeds

Seaweed is the common name for macroscopic marine algae that includes members of the red, brown, and green algae (Fig. 1). The term “kelp” generally refers to genera of larger brown algae (Emery, 1963) that typically flourish in cooler waters of high latitudes and in areas of strong upwelling (McGill, 1958; Mann, 1973). Seaweed distribution is mainly controlled by physico-chemical conditions of an environment, including water temperature, water turbidity, nutrient levels, and bottom topography (Emery and Tschudy, 1941; Bolton and Levitt, 1987). Most seaweed is confined to shallow water (maximum depth of 30 m; Smith and Bayliss-Smith, 1998) with the exception of giant kelp species such as *Macrocystis pyrifera*, which grows up to 60 m long (van den Hoek et al., 1995). Seaweeds anchor to stable substrata such as bedrock, boulders,

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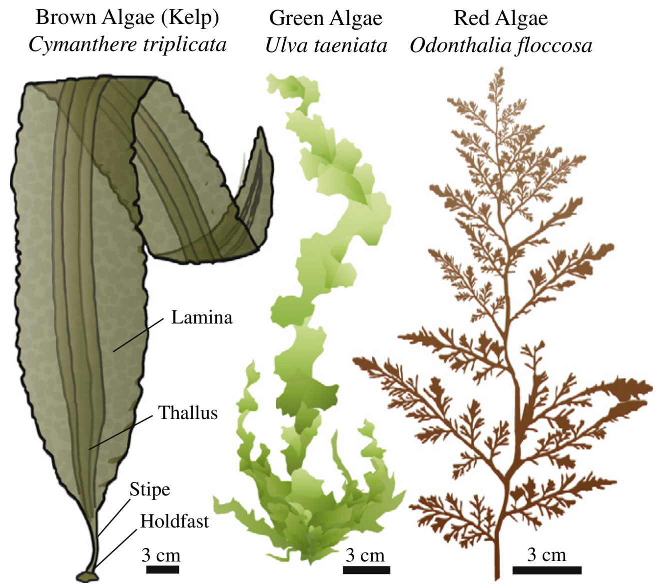

Fig. 1. Schematic diagrams of the seaweeds involved in gravel transport in the Juan de Fuca Strait. The brown algae (kelp) *Cymanthere triplicata* is associated with benthic gravel transport, whereas green and red algae (*Ulva taeniata* and *Odonthalia floccosa*, respectively) are associated with wave-induced gravel transport onto land.

and cobbles, and will even attach to the holdfasts and stipes of mature kelp plants.

For seaweed-assisted gravel transport, seaweeds must grow on gravel-bearing substrates where holdfasts are anchored to individual clasts or groups of clasts. Three species of seaweed aided in gravel transport in the Juan de Fuca Strait, western Canada: *Cymanthere triplicata* (brown algae/kelp), *Ulva taeniata* (green algae), and *Odonthalia floccosa* (red algae; Fig. 1). Of these, only *C. triplicata* was observed dragging gravel clasts across the seafloor. *U. taeniata* and *O. floccosa* were only observed attached to intertidal gravel clasts that were presumably deposited onshore by waves.

1.2. Study area and methods

The southwest coast of Vancouver Island, Canada, along the Juan de Fuca Strait experiences relatively few large ocean swells, mainly because it is protected from full-ocean swells by the Olympic Peninsula, Washington, USA (Fig. 2). The dominant fairweather wind and wave direction are from the southwest, and spring tides at the coastline are mesotidal (average tidal height: 2.2 m; Davenne and Masson, 2001). The tidal system is diurnal, although the amplitude of the second high and low tide is reduced. Strong flood- and ebb-tidal currents flow parallel to the shoreline along the Juan de Fuca Strait, reversing direction twice daily.

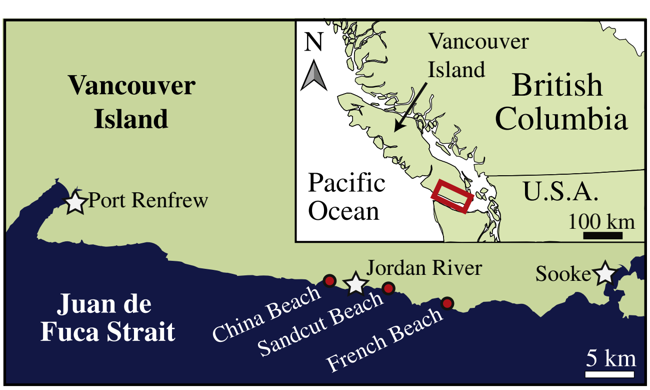

Fig. 2. The Juan de Fuca Strait, British Columbia, Canada. The location of the three beaches where SABGT was observed is shown. Current velocity data presented in Fig. 4 is from 13 m water depth off of French Beach.

Seaweed-assisted, benthic gravel transport was observed on the shoreface of three composite sand-and-gravel beach–shoreface complexes, (French Beach, Sandcut Beach, and China Beach) between the towns of Sooke and Port Renfrew (Fig. 2). Qualitative observations of SABGT were made in 2008 while SCUBA diving to 13, 18, and 23 m water depth (relative to mean spring high tide (MSHT)) offshore of three beaches along the strait. In 2009, three doppler meters were deployed in the Juan de Fuca Strait (one doppler meter per beach), and local current and wave data was measured at each site. The doppler meters, which had to be deployed and retrieved with the aid of SCUBA diving, continually collected data from June to August 2009. During the SCUBA-assisted recovery of the meters, seaweed-assisted, benthic gravel transport was documented and photographed off of French Beach (Fig. 3). Using the time that SABGT was observed, and the velocity measurements and time from the doppler meter at French Beach, it was possible to establish the current velocities under which the gravel clasts were transported. Doppler meter data were evaluated using the program Storm® produced by Nortek Inc.

2. Results

In the summer 2008, during successive dives at 13 m, 18 m, and 23 m water depth (relative to MSHT), it was observed that gravel clasts with attached seaweed (generally one frond per clast) were being dragged along the seafloor by tidal currents within the Juan de Fuca Strait (Fig. 3 A–C). In all cases, the attached seaweed was horizontal or nearly horizontal to the bed. The clasts anchoring the seaweed were large pebbles to cobbles (3 to 6 cm along the b-axis, up to 10 cm along the a-axis; Fig. 3) and the attached seaweed was *Cymanthere triplicata*. Clast transport was entirely shore parallel in the direction of tidal flow, and onshore-directed motion due to wave orbital flow was not observed. Motion of the clasts was both directly observed and inferred from furrows left in the sediment behind the clasts (Fig. 3C).

In August 2009, SABGT was observed off of French Beach in 13 m water depth during recovery of the doppler meter deployed there. The doppler meter provided measurements of current velocities at the time of SABGT. At the time of observation, the tide seaward of French Beach was in the late flood stage of the weaker semidiurnal tide. The velocity of the water column was relatively uniform at 0.3 m s^{-1} from the surface to the sediment–water interface (Fig. 4). Wave-generated current velocities were measured up to 4.3 m s^{-1} (maximum). The maximum tidal current velocity recorded in the Juan de Fuca Strait (at 13 m water depth) from June to August 2009 was 0.8 m s^{-1}.

3. Discussion

3.1. Gravel transport mechanisms in the Juan de Fuca Strait

Gravel transport in the Juan de Fuca Strait can occur as a result of both wave and tidal processes. Maximum wave-generated current velocities measured at 13 m water depth off of French Beach during the summer 2009, were 4.3 m s^{-1}, which is sufficient to re-mobilize gravel up to 4 cm diameter (Fig. 5) and carry them from the shoreface to the beach. The presence of an algal "sail" (Kudrass, 1974) on sediments in the upper shoreface and intertidal zone undoubtedly increases coarse sediment transport landward (Emery and Tschudy, 1941; Smith and Bayliss-Smith, 1998). Wave processes are stronger at shallow-water depths, and typically dominate sediment transport in water 5 m deep and less. Although tidal currents are still flowing at shallow depths, and may contribute to gravel transport, waves are the dominant sediment transport process (Frey and Dashtgard,