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Natural and human impacts on centennial sediment accumulation patterns on the Umpqua River margin, Oregon

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ABSTRACT

Quantifying patterns of sediment accumulation rates (SARs) over the past ~125 years on continental margins provides insight into diverse processes spanning the land–ocean boundary. In particular, temporal changes in the export of fluvial sediment can lead to changes in ocean margin SARs, whereas spatial patterns of accumulation reflect the net effect of wave-driven resuspension and current transport averaged over many years. To explore these issues we quantified SARs using ^{210}Pb geochronology at 73 stations on the shelf and upper slope off the Umpqua River, Oregon. Three types of ^{210}Pb profiles were observed: a well-defined roughly 10-cm-thick surface mixing layer (SML) underlain by a zone of logarithmic decrease on the distal mid to outer shelf and slope (type 1, $n = 45$); a deep (20–30-cm thick) SML underlain by a zone of logarithmic decrease in the sandy inner shelf (type 2, $n = 8$); and a composite profile with two distinct zones of logarithmic decrease below an ~10-cm-thick SML in a mid-shelf depocenter adjacent to the river mouth (type 3, $n = 21$). Type 3 profiles imply a 2–4-fold increase in the SAR that occurred, on average, in 1967 ± 13 y. Such an increase in SARs is consistent with the history of industrial logging in the Umpqua basin, which peaked in the two decades after World War II and coincided with a wet phase of the Pacific Decadal Oscillation (1944–1978) when average and peak river flows were elevated. Comparison of the Umpqua River shelf depocenter with the well-studied Columbia and Eel River systems reveals some important similarities and differences between these 'marine-dispersal dominated' systems, whereby forcing (e.g., river–ocean coherence) on the Umpqua is comparable to that of the Eel, whereas the spatial pattern is more similar to that of the Columbia. These seemingly paradoxical results can be reconciled by considering the *relative* significant wave height during periods of elevated sediment delivery.

1. Introduction

Spatial and temporal patterns of sediment accumulation on continental margins provide important information on processes occurring across the land–ocean boundary and are key to understanding whole-margin geology and biogeochemistry. Variations in sediment supply from uplands due to both natural (e.g., seismic, volcanic; Major et al., 2000; Hovius et al., 2011) and anthropogenic (e.g., land use, fire; Pasternack et al., 2001; Warrick et al., 2012) perturbations can be recorded in offshore sedimentary sinks (e.g., Gomez et al., 2007; Sommerfield and Wheatcroft, 2007). Because fluvial sediment supply is a fundamentally integrative process, deciphering supply fluctuations yields valuable information on the connectivity of sediment routing systems (e.g., Allen, 2008; Jerolmack and Paola, 2010) and provides context for the delivery of diverse bioactive constituents (e.g., Wheatcroft et al., 2010; Hatten et al., 2012; Goñi et al., 2013). Once delivered to the coastal ocean, sediment undergoes a second set of processes that determines its initial pattern of deposition and eventual accumulation. Thus, patterns in wave energy, along- and across-shelf currents, and shelf physiography can have important effects on sediment dispersal and accumulation (e.g., Wright and Nittrouer, 1995; Geyer et al., 2004; Walsh and Nittrouer, 2009). Due to the complexity of these processes a general, predictive theory of margin sedimentation has yet to be formulated.

All of the forcing processes mentioned above vary on a range of timescales and, because sediment accumulation rate also varies as a function of observation time (Sadler, 1981; Schumer and Jerolmack, 2009), it is important to stipulate the time scale of interest. Herein, our concern is sediment accumulation on decadal to centennial timescales over the past ~125 y. There are three reasons for this focus. First, this period of time is when relatively complete historical records of important processes (e.g., rainfall, river discharge, logging intensity) exist, thus there is the potential of establishing rigorous cause-and-effect relationships that can be used to decipher pre-historic sediment archives. Second, in the Pacific Northwest, the location of our research efforts, the period of time from the late 19th century to the present has been when human effects on the landscape have been most pronounced. The brevity of

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large-scale human impacts in our study area contrasts with the situation in many other parts of the globe where anthropogenic effects have existed for centuries to millennia (e.g., Pasternack et al., 2001; Oldfield et al., 2003; Gomez et al., 2007). Lastly, studying sediment accumulation over decadal to centennial timescales is facilitated by the existence of ^{210}Pb, a particle-reactive, naturally occurring radionuclide that has a half-life of 22.2 y, and therefore records processes over the past ~125 y (Robbins, 1978; Nittrouer et al., 1979).

Our focus is to document and understand patterns of sediment accumulation over decadal to centennial time scales on an active continental margin, in particular the upper slope and shelf off the Umpqua River, Oregon. Studies of the Umpqua, a small, mountainous river (SMR) system, provide an opportunity to add to the growing body of knowledge on this type of river dispersal system (Nittrouer, 1999; Wheatcroft, 2000; Carter et al., 2010). Doing so is important, because SMRs supply roughly 50% of the sediment to the global ocean (Milliman and Farnsworth, 2011) and a similar fraction of bioactive constituents, in particular particulate organic carbon (e.g., Lyons et al., 2002; Hatten et al., 2012; Goñi et al., 2013). Although much is known about SMRs and how they differ from large river systems, we still lack an appreciation of how variations in key parameters combine to determine the location and character of margin depocenters (e.g., Walsh and Nittrouer, 2009). This lack of understanding arises for two reasons. First, the realization that SMRs are globally significant is a relatively recent one, thus the number of detailed case studies is small compared to the potential diversity of system behaviors (i.e., we are data starved). Second, as noted above, there is a general lack of theory by which to categorize SMRs.

A recent compilation of river dispersal systems by Walsh and Nittrouer (2009) is an important advance toward a theoretical understanding of margin sedimentation. In this study, river sediment load, mean significant wave height, tidal range, and shelf width were used to identify five types of river dispersal systems. Of the five, the most common were 'proximal accumulation dominated' (PAD) and 'marine dispersal dominated' (MDD) systems, with the former defined on the basis of low wave and tidal energies. In contrast, MDD systems are characterized by high wave and/or tidal current energies that preclude deposition proximal to the river mouth and cause efficient along- and across-shelf sediment dispersal. Because of the energetic wave conditions along the US West Coast (Allan and Komar, 2006), all river dispersal systems in the region were classified as MDDs (Walsh and Nittrouer, 2009).

The objectives of this paper are threefold. First, we seek to quantify sediment accumulation rates over the past 125 y on the shelf and upper slope (<200 m) off the Umpqua River. Because spatial gradients in SARs can be large on continental shelves (e.g., Sommerfield and Nittrouer, 1999), a high-density array of stations was studied. Second, we interpret the patterns of sediment accumulation, both in space and time, in light of potential natural and anthropogenic forcings. Specifically, we are interested in determining whether large-scale timber harvesting in the Umpqua River basin has had a measurable impact on the accumulation of sediment on the continental margin. Third, we compare our results to other marine dispersal dominated systems on the U.S. West Coast (e.g., Columbia and Eel Rivers) with the aim of further refining this important class of sediment dispersal system.

2. Methods

2.1. Study area

The Umpqua River drains a 12,103-km^2 mountainous basin that heads in the High Cascades (maximal elevation: Mount Thielsen, 2799 m) and then flows through the Western Cascades, Klamath Mountains, and Oregon Coast Range (OCR) before discharging into the Pacific Ocean around 43.7° N. The geology, geomorphology, and sediment production of the Umpqua basin are varied (Fig. 1a, b), with the permeable, low-relief volcanic rocks of the High Cascades resulting in little runoff and sediment production (Jefferson et al., 2010), whereas the more deeply dissected mountains of the Western Cascades support higher rates of runoff, with mass wasting the dominant mechanism of hillslope sediment erosion (Grant and Wolff, 1991). Further west, the South Fork of the Umpqua River passes through the rugged Klamath Mountains, which comprise a complex assemblage of meta-sedimentary, volcanic and intrusive igneous rocks with variable sediment production rates (Wallick et al., 2011). Lastly, the mainstem Umpqua River flows through the OCR, which in the Umpqua basin is composed of the Paleocene to Eocene soft marine sediments of the Elkton and Tyee Formations (Molenaar, 1985); both of which are susceptible to landsliding (e.g., Roering et al., 2005).

Except for its central portion, the Umpqua River basin is densely forested with Sitka spruce and western hemlock dominating near the coast and Douglas-fir elsewhere (Franklin and Dyrness, 1973). Since colonization by Euro-Americans in the mid 19th century a range of land use activities, including placer mining, in-stream gravel mining, farming, ranching, and timber harvesting, have occurred in the basin that may have altered sediment production and transport (Wallick et al., 2011). Of these land uses, timber harvesting has likely been the most important. For example, Douglas County, whose boundaries follow closely that of the Umpqua basin, ranked second in the nation in timber production from 1949 to 1970 (Wall, 1972). A recent analysis of Landsat imagery by Cohen et al. (2002) indicates that approximately 18% of the forested portion of the Umpqua basin was logged between 1972 and 1995 (Fig. 1c). Because this was a period of declining timber harvest in the region (discussed below), we can expect that the cumulative watershed effects of logging, which included extensive road building, log 'drives' and splash damming (Brown and Krygier, 1971; Reid and Dunne, 1984; Miller, 2010), to have been potentially greater in earlier parts of the 20th century.

The Umpqua River basin's climate is highly seasonal, with wet, stormy winters (NDJFM) and relatively dry summers (AMJJASO). Average annual precipitation (1971–2000) ranges from ~800 mm/y in the interior lowland portion of the basin to >2700 mm/y in the OCR (Fig. 1d). Peak flows measured at the U.S. Geological Survey's gauging station near Elkton (station number 143210), which captures runoff from ~79% of the basin, are due to winter frontal systems (i.e., 'atmospheric rivers,' Ralph et al., 2006; Dettinger, 2011), with the largest flows resulting from rain-on-snow events. During the period of record (1905–present), the largest measured flow was during the December 1964 flood, when discharge reached 7505 m^3/s. This flood was likely the highest in the basin since the rain-on-snow event of 1861 (Wallick et al., 2011). Since the 1950's several hydroelectric and flood-control dams were constructed mainly in the North Fork of the Umpqua, but also in the Upper Cow Creek basin. Because these dams are in the upper part of their respective basins they likely have little impact on the mainstem discharge measured at Elkton (Wallick et al., 2011).

As mentioned above, sediment production within the basin varies as a function of geologic province. To estimate the relative contribution of different parts of the basin to total sediment load, we used data compiled by Curtiss (1975) from five gauging stations in the basin (Fig. 1b). The estimated load at the mainstem station (143210, 'Umpqua River near Elkton') is 3.2 Mt/y, with contributions of 1.5 Mt/y and 0.7 Mt/y from the South and North Forks of the Umpqua, respectively (stations 143120 and 143195). Subtracting these amounts from the Elkton load provides an estimate for the 1733-km^2 portion of the basin between the South and North Fork stations ('between stations'; Fig. 1b) and the Elkton station of 0.9 Mt/y (yield = 525 t/km^2/y). To estimate the load of the 2564 km^2 area downstream of Elkton, which includes the Smith River, Elk Creek and numerous other tributaries draining the OCR, we have averaged the yield obtained from stations