Paradox of downstream fining and weathering-rind formation in the lower Hoh River, Olympic Peninsula, Washington

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ABSTRACT

Although downstream fining of clasts is typical in modern and ancient river systems, the Hoh River, a cobble-and-boulder-bed river in Washington state, contains surprisingly little downstream fining of the coarsest tail of the grain-size distribution along its lower 63 km. Mean rate of fining of the coarsest size fraction is only 0.24 mm/km, barely significant given uncertainties in measurement. In addition, these same clasts have weathering-rind thicknesses that change very little along the length of the river (they decrease by 0.01 mm/km). Because weathering rinds are well developed in this setting and both tumbler studies and field observations show that abrasion of weathering rinds greatly accelerates clast diminution, there seems to be a paradox between predicted and observed downstream fining rates. Field study shows that detritus is constantly being resupplied to the river by erosion of late glacial materials along the river’s cutbanks and tributaries. The clasts supplied range in size but include abundant coarse grains with very thick weathering rinds. The continuous resupply of grains strongly attenuates the rate of downstream fining, despite the fact that these weathered grains abrade relatively rapidly. Thus, the dominance of reworked glacial debris overwhelms any processes by which grains are reduced in size in the modern river. These results suggest that relatively infrequent glacialization can have a long-lived effect on river sedimentation.

Keywords: gravel, Hoh River, Olympic Mountains, Washington, fluvial, sedimentation, downstream fining, geomorphology.

INTRODUCTION

Downstream fining is common in river channels. The processes of selective deposition of the coarser clasts and abrasion lead to reduction of grain size along the length of river systems. Selective deposition refers to the trapping of the coarsest grain sizes in a river channel, primarily as bars, patches, and bedload sheets (e.g., Ashworth and Ferguson, 1989; Parker, 1991; Paola et al., 1992). As the coarsest grains are preferentially removed, the overall grain-size distribution becomes finer downstream. Mechanical abrasion of clasts during transport also leads to decreased grain size downstream. Tumbler (abrasion mill) studies, however, indicate that this process is quite slow and may not explain the rapid rate of downstream fining observed in natural streams (Plumley, 1948; Shaw and Kellerhals, 1982; Kodama, 1994; Jones and Humphrey, 1997). Bradley (1970) suggested that floodplain storage and weathering-rind development can be an important mechanism (Kuenen, 1956; Jones and Humphrey, 1997) for downstream fining.

To test these ideas, we studied downstream fining along the lower Hoh River, in coastal Washington state. This area is characterized by temperate rainforest, with commensurate high rates of vegetation growth, rainfall (average 318 cm/yr), river discharge (average annual peak discharge since 1960 is 4075 m³/s), and moderate rates of soil development. All of these characteristics suggest a setting conducive to rapid downstream fining by Bradley’s mechanism. However, preliminary investigation of the Hoh River revealed a notable lack of fining over the observed river length. The difference between expected and observed rates of downstream fining inspired us to investigate the mechanisms that might retard downstream fining.

HOH RIVER

The Hoh River drains part of the western flank of the Olympic Mountains (Fig. 1). Headwaters include Mount Olympus, reaching 2428 m in elevation. From there the river follows a 75 km course to the Pacific Ocean. The Hoh River has a gravel bed along its entire length. We studied the lower 63 km of the river, which includes the alluvial, flood-plain-dominated part up to where the flood plain

Figure 1. A: Map of Olympic Peninsula, Washington state, showing location of Hoh River and metasedimentary rocks of Olympic core. Core rocks are those at prehnite-pumpellyite grade or higher (from Tabor and Cady, 1978). B: Map of lower Hoh River, showing sample sites and distribution of glacial deposits (shaded) perched in terraces above valley floor.

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significantly narrows toward the core of the Olympic Mountains. Along this length, the river exposes a variety of bars during low-flow conditions (base flow 1565 m³/s). Channel width during low flow is typically less than 100 m. Average river slope along the studied reach is $3 \times 10^{-3}$, and average sinuosity is only 1.3. The valley floor is relatively undisturbed by human impact.

The river flows in an incised valley for nearly its entire length. In the study area, glacial deposits are dissected to varying degrees, have cut banks. Long-term rock uplift rates range from about 0.1 mm/yr along the coast to 0.83 mm/yr in the Olympic core (Pazzaglia and Brandon, 1996). Despite the overall incisional nature of the river valley, there have been episodes of aggradation in the past (Thackray, 1995), as evidenced by floodplain deposits formed over the past few centuries, and today there are zones where the channel belt widens significantly and where many mid-channel bars are deposited.

In the study area, the river erodes down into Tertiary bedrock at several places. Inner gorges that cut through bedrock exposures are as deep as 10 m or more along this sector. Bedrock incision near the coast may, in part, reflect local young uplift (Thackray, 1998).

The ultimate source area for at least the coarsest gravel fraction is dominantly upstream of the study area (Fig. 1). The most durable clasts are primarily very fine grained to medium-grained turbidite sandstones that have a low-grade metamorphic overprint (Tabor and Cady, 1978). A minor component (<4%) of the coarse gravel consists of slate and vein quartz clasts. The source area for all of these rocks includes the Western Olympic Lithic Assemblages of Tertiary age that compose much of the range (Tabor and Cady, 1978). Rocks of this assemblage, and the younger Hoh Lithic Assemble, form the lower Hoh River valley walls, whereas the more durable rocks, of higher metamorphic grade, are dominantly found upstream of the confluence with the south fork of the river (Fig. 1).

Much of the flood plain and valley-fill remnants (late glacial–Holocene) is gravel. Gravel storage occurs as the meander belt migrates and/or avulses across the narrow flood plain and bars are abandoned. Map comparisons along two stretches suggest meander-migration rates greater than 3 m/yr; however, some of this meander migration could occur during the floodplain width of 0.3 to 1 km, suggesting an average residence time of 160 to 300 yr between the time when gravels are first stored and when they are exhausted as the next meander loop passes through.

**METHODOLOGY**

Our goal was to examine the role of floodplain storage of river gravel, attendant weathering-rind development, and subsequent reworking and abrasion on downstream-fining rates along the lower Hoh River. To document the rate of downstream fining, we sampled gravels from bars along the length of the river at a spacing of about 8 km. To document changes in the maximum grain size, we developed a strategy for characterizing the coarse tail of the distribution. Exposed parts of bars were relatively unvegetated and ranged from 180 m to about 1 km long and were about 25 to 50 m in maximum width. At each bar, we located what appeared to be the coarsest sector of grain sizes that occurred near the exposed point of the bar farthest upstream. At this point on the bar, we collected about 100 rocks at 25 cm spacing. We measured intermediate-axis diameter, identified rock type (grain size, composition, and fracturing), and measured minimum and maximum weathering rinds normal to the outer surface (Fig. 2A). We avoided measuring rinds around tight curves in the rock surface, where weathering rinds are thicker than for two- and three-dimensional effects. Replicate sampling showed operator consistency of >98% on diameter and >93% on rind-thickness measurements. Fresh rocks were devoid of weathering rinds. Stained rocks contained only an exhalation.

We collected data from gravels from the flood plain and from older glacial deposits in cut banks and barrow pits. From these sites, we also counted tree rings on the oldest growth trees on these surfaces in order to estimate the age of deposition. Finally, we collected gravel samples from modern bars; these were tumbled in the lab to determine diminution rates of different clasts.

**FIELD RESULTS**

**Downstream-Fining Rates**

Our data showed very little downstream fining of the coarse fraction on the bars (Fig. 3A). Mean size of the samples at the upstream points in the river ranged from 80 to 106 mm in $b$-axis diameter, whereas downstream, along the first 11 km from the river mouth, the average grain size of this coarse-tail fraction was 64–99 mm (Fig. 4A). This minimal change, especially given the overall distribution of sizes, suggests little, if any, change in the coarse-tail grain size on the bars.

**Rind Thickness Data**

Rind thickness data likewise showed little variation along the length of the river (Fig. 3B). Rinds measured in modern bars ranged from 0 to 7 mm thick, on average (Fig. 4B). Our results show some control by lithology: the medium-grained sandstones contain the thickest rinds, probably owing to higher per-
meability. Other measured lithologic controls, including percentage of mica and presence of fractures, did not appear to correlate with weathering-rind development. Of the totally weathered clasts, 58% were in medium-grained sandstones and 48% were in micaceous sandstones, but only 27% of the totally weathered clasts were in rocks described as containing fractures.

There seems to be some difference in rind thickness between clasts in the modern bars and those in the older sediment in the cutbanks and barrow pits above the river (Fig. 5A). The older deposits contain, in general, thicker weathering rinds (8.6 mm, on average), not including those grains completely weathered through (up to 24% of total, Fig. 5B). Rinds developed on gravels found beneath 28-yr-old trees (from tree-ring measurement) at km 59 contain rind-thickness distributions similar to the much older glacial deposits (Fig. 5). Although tree-ring ages represent the minimum age of this low terrace, the contained gravels are unlikely to be more than a few decades old. We refer to these gravels as “decadal deposits.” Nearly all grains in the old deposits had weathering rings.

ABRASION STUDY
A goal of this study was to examine the role of floodplain weathering on the rate of downstream fining in the river. We collected weathered clasts from bars along the Hoh River and then tumbled them in the lab, to look at relative abrasion rates between fresh and weathered grains (cf. Kuenn, 1956; Bradley, 1970; Jones and Humphrey, 1997).

The tumbling mill, a plastic-lined steel drum, 0.56 m in diameter, was mounted with its spin axis at 20° from horizontal. The drum interior contained four plastic vanes, 2 cm high, with which to agitate particles. Water was added, to ensure that grain collisions would take place dominantly under water, and the drum was rotated at 6.8 rpm. Although it is difficult to precisely equate tumbling duration in the drum with distance of transport in the river, a comparison can be made by using rotation rate and inner circumference (an approximation used by Wentworth, 1919). This approach suggests that the mill simulates about 0.7 km of river transport per 1 h of tumbling.

The abrasion study used two groups of gravel clasts from the Hoh River having significant rind thickness and 12 fresh, or stained, clasts. These particles were first measured (mass and a, b, and c axis lengths) and then tumbled as a group; they were removed and remeasured after 2, 6, 14, 20, and 62 h of tumbling (Fig. 6). The rate of diminution of the fresh clasts was nearly constant over time and, in all but one case, was fairly slow (0.44 g/h on average [Fig. 6B], equivalent to 0.62/km if the time-distance equivalence already mentioned is used). In contrast, the clasts with weathering rinds generally decreased in size much more rapidly owing to abrasion (7.3 g/h on average), at least until the weathering rind was removed, after which the rate of diminution slowed (Fig. 6A).

DISCUSSION
Our results indicate that the coarse-tail fraction of grains exposed along bars does not vary much along the length of the lower Hoh River. Throughout the study area, the mean coarse-tail grain size is cobble. Mean size at the most upstream site (km 63.5) is 96 mm, identical to the most downstream site (km 3) (Fig. 4A). However, means range nonsystematically from 64 to 106 mm along the river. The mean rate of decrease in grain size is 0.24 mm/km, or a total of 16 mm over the length of the study area. We consider this difference to be barely significant, given uncertainties in measurement and the range of 95% confidence level on calculation of site means (±7.1 to 12.4 mm, Fig. 4A). Nonetheless, the average rate of downstream fining does not differ greatly from the results from the tumbler study (0.24 mm/km in the river vs. 0.62 mm/km).

Weathering-rind thicknesses also do not change downstream (Figs. 3B and 4B). Average rind thicknesses range from 3.8 mm (at km 18.5) to 6.6 mm (at km 42.5). The rate of decrease in rind thickness downstream is about 0.01 mm/km (Fig. 4B), statistically insignificant, given the uncertainties in the measurements and the range of observations.

Weathering rinds in the older deposits (Fig. 5A) show a slight increase over those from
modern bars (Fig. 3B). Maximum rind thickness from the older deposits averages, as a group, 8.6 mm, not including clasts completely weathered through (16% of all clasts counted). In contrast, the average maximum rind thickness along modern river bars is 5.0 mm, not including the completely weathered clasts (11%). More important is the occurrence of totally fresh samples in these older deposits. Neither the decadal deposits nor the glacial-age deposits had more than 3% clasts that were either completely fresh or only slightly stained (Fig. 5B); however, in all but one of the modern bars (Fig. 5B), between 15% and 30% of clasts counted were fresh or only stained. That is, if gravels are derived from reworking of older deposits, then weathering rinds are removed by the modern stream.

Controls on Downstream Fining

From the lack of change in grain size and weathering-rind thickness along the length of the river system, one might interpret that clasts do not abrade much during stream transport. In contrast, our tumbling-mill work, as well as that of Jones and Humphrey (1997), shows that weathering rinds facilitate the effectiveness of abrasion, weathered clasts having fining rates at least an order of magnitude faster than those of fresh clasts (Fig. 6). It is quite likely that river abrasion removes weathering rinds during transport, a possibility supported by field observations of clasts with rinds thinned and locally removed (Fig. 2B).

As the tumbler study demonstrates, fresh clasts fine at much slower rates than do weathered clasts. Without the field-based results, one might think that downstream fining is slow because most clasts in transport are fresh. However, most Hoh River samples measured contained weathering rinds. Given that the range of weathering-rind thicknesses on the modern bars and the range on older deposits overlap considerably, it seems likely that many of the clasts still bore their weathering rinds from when they were stored in the flood plain. We found weathering rinds on clasts that show clear evidence of multiple storage and reworking (Fig. 2, C and D). This result means that, at least to some extent, weathered clasts were removed from the active system before their weathering rinds were completely removed. Thus, a process involving rapid removal of weathering rinds from clasts followed by very slow downstream fining of their unweathered cores plays a minor role in downstream fining in this system.

We suggest that an alternative way to inhibit the measured rate of downstream fining yet maintain the thickness of weathering rinds is to continuously replenish the supply of coarse, weathered clasts along the entire length of the river system. In this scenario, abrasional fining is actually very rapid, at least for the weathered parts of clasts. If no other source of clasts existed along the system, this process would yield rapid downstream fining, as seen in the tumbler study. However, the entire length of the Hoh valley is mantled in glacial deposits, either till or outwash (Tabor and Cadby, 1978; Thackray, 1995). This material is variably sorted but dominated by strongly weathered clasts (Fig. 5). The river intermittently taps into these minor, irregularly distributed sources, commonly along cutbanks of meander bends or by mass wasting along low-order tributaries. These sources provide material of size and weathering-rind development that exceeds the grain sizes measured along the adjacent stretch of river. Because the measured river gravel is, on average, finer and contains thinner weathering rinds, these introduced clasts must rapidly break down by abrasion within a short distance, probably a few bars, in the stream.

These large clasts with only partially removed weathering rinds make up the coarsest, least mobile fraction of the bars. Because we primarily sampled this coarse fraction, we observed little downstream fining. Our sampling of the lower, alluvial, reach leads to an appearance of retarded fining because the only significant source of large clasts is cutbank erosion of flanking terraces that, in themselves, have very gradual downstream fining. This continuous resupply of weathered coarse material and its rapid abrasion strongly smooth the distribution of grain-size and weathering data measured along the river. The result is a strongly uniform data set along the entire length of the river.

SUMMARY

Our results confirm the importance of abrasion of weathering rinds as a means of accelerating downstream fining in river systems. Rapid diminution coupled with continuous resupply of coarse clasts means that studying only the largest size fraction can lead to results that are not representative of the entire grain-size distribution.

Trends of grain-size fining in fluvial systems have been used as an indicator of tectonic uplift and erosion of source areas (i.e., syntectonic sedimentation). However, our observations from the lower Hoh River suggest that inheritance of older deposits can play a dominant role in downstream fining (or absence thereof), at least in glaciated terrain. To the degree that the formation of glaciers is associated with mountain building, the areas most expected to have a strong syntectonic signature in the form of river deposition of coarse clasts and slow rates of downstream fining (Heller et al., 1988; Paola, 1988) are precisely the areas where this signature can be diluted by reworking of older deposits. It seems that even the simplest systems can be out of equilibrium with long-term rates of uplift and base-level change. Our understanding of downstream fining mechanisms derived from recent characteristics may have little to do with the controls on fining seen in the long-term sedimentary record.

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