Sediment storage and evacuation in headwater valleys at the transition between debris-flow and fluvial processes

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ABSTRACT

Sediment from landscape disturbance often enters temporary storage in valleys and evacuates over longer times, which in steeplands are poorly delimited. We hypothesize that, across process transitions (e.g., debris flow versus fluvial transport), distributions of sediment transit times also change. We use field surveys and extensive radiocarbon dating to assess the distribution of transit (residence) times through the proxy measurement of ages of bank deposits in two mainstem reaches of a 2.23 km^2 watershed in the Oregon Coast Range. In the downstream reach, debris fans impound fluvial deposits; debris-flow, fine fluvial, and coarse fluvial deposits compose nearly equal parts of the valley fill; and fluvial erosion evacuates deposits. Transit times have a sample mean of 1.22 × 10^3 ^{14}C yr and an exponential distribution, indicating uniform probability of evacuation from storage. In the upstream reach, valley-spanning debris jams impound debris-flow deposits composing >95% of the valley fill, which is routinely scoured by debris flows. Transit times have a sample mean of 4.43 × 10^2 ^{14}C yr and, if >100 ^{14}C yr, a power-law distribution, indicating preferential evacuation of younger deposits and retention of older deposits. In both reaches, most sediment has short transit times (<600 ^{14}C yr), but significant volumes remain for millennia. Less than 20% of basin-wide denudation passes through these reservoirs, but the latter are still significant buffers between hillslope disturbance and downstream aquatic habitat, especially for coarse sediment.

Keywords: sediment budget, residence time, debris flows, fluvial transport, radiocarbon dating, stratigraphy.

INTRODUCTION

Anthropogenic changes to sediment supply, caliber, and transport capacity can degrade sensitive riverine habitats, particularly for salmonids (e.g., Montgomery et al., 1996; Soulsby et al., 2001; May and Lee, 2004). Degradation may be magnified at transitions where one transport process ends and another begins. Specifically, in steeplands debris flows scour and transport large quantities of unsorted sediment stored in steep valleys and deposit them en masse in lower gradient fluvial networks (e.g., Lancaster et al., 2001, 2003; Eaton et al., 2003; May and Gresswell, 2004). Where landscape disturbance (e.g., logging, fires) releases sediment, some fraction is stored in the steep valley network (e.g., Gilbert, 1917). This stored sediment is evacuated by erosive debris flows and by fluvial entrainment following collapse of woody debris dams (May and Gresswell, 2003; Montgomery et al., 2003; Lancaster and Grant, 2006), avulsion, and bank erosion. Sediment storage volumes and transit times determine both the magnitude and duration of downstream effects of landscape disturbance but are largely unconstrained.

Benda and Dunne (1997a), Lisle and Church (2002), and Malmon et al. (2003) hypothesized that a fixed percentage of stored sediment is evacuated during a given time interval so that all sediment in a given storage element (e.g., floodplain, terrace) has equal probability of evacuation. It follows that distributions of sediment transit times (i.e., times between deposition and evacuation) are exponential for steady-state reservoirs. Alternatively, Nakamura and Kikuchi (1996) found that, because older sediments often remain at valley margins, the likelihood of erosion was inversely related to deposit age: more sediment is evacuated after short times, but older sediments persist for longer, as in a power-law distribution of transit times (Bolin and Rodhe, 1973). As results from landscape-scale models of debris flows and fluvial sediment transport begin to influence land-use practices and stream restoration, we need to understand how much sediment is stored and the characteristics of its release (e.g., Benda and Dunne, 1997a, 1997b; Lancaster et al., 2001, 2003).

We examined sediments deposited by streams and debris flows in a headwater valley in Oregon. Here we use systematic cross sections and radiocarbon (^{14}C) age estimates of deposits to estimate volumes of stored sediment and model distributions of transit times. We interpret bank stratigraphy to characterize deposition and evacuation mechanisms prevalent in our field site. Using nearby lowering rates, we estimate what fraction of annual sediment load to the valley enters storage. This number and the modeled distribution of transit times characterize the system's response to disturbance-derived sediment loading.

STUDY SITE IN THE OREGON COAST RANGE

The Bear Creek basin (Fig. 1) is cut into thick-bedded, shallowly dipping, Eocene sandstone of the Tyee Formation (Peck, 1961). Valley side slopes of 84% (40°) are typical. Dense networks of valleys above ~3%–10% (2°–6°)

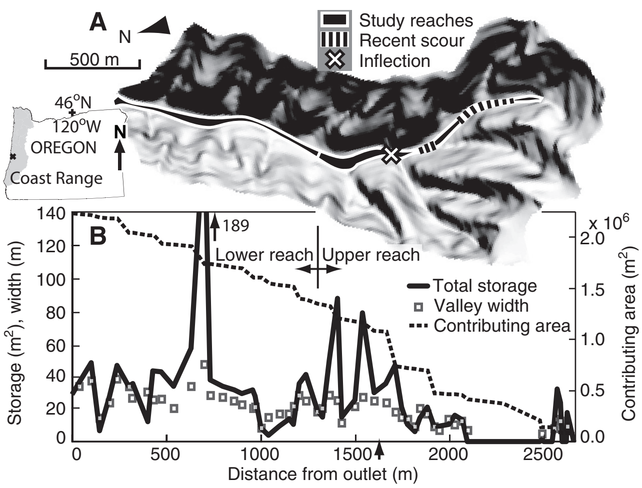

Figure 1. A: 10 m shaded relief map of Bear Creek basin, Oregon Coast Range, showing upper and lower study reaches (outlined in white). Hachures show locations of recent debris-flow scour. X (and arrow on distance axis in B) shows location of debris-flow–fluvial transition from power-law fitting method of Stock and Dietrich (2003); results of other methods were ambiguous. B: Cross-sectional areas of sediment stored above bedrock valley floor; valley width (distance between valley walls on deposit surface) at cross sections; and contributing area (measured using 10 m digital elevation model) versus streamwise distance from the outlet (same horizontal scale as A and aligned to division between upper and lower reaches). Cross-section spacing is varied (average 40 m, σ = 19 m) to best capture deposit volumes.

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slope are likely dissected by debris flows from shallow, rapid landslides (Stock and Dietrich, 2003; Roering et al., 2005), typically initiated during prolonged winter rainfall (Montgomery et al., 2000).

Bear Creek's thalweg runs over bedrock for much of its length and commonly exposes the full depth of valley-floor deposits as cut banks. This exposure, perhaps due to the relative dearth of recent disturbance in Bear Creek (May and Gresswell, 2004), allows accurate estimations of the total sediment volume in storage and adequate access to samples for ^{14}C dating, but may indicate some bias toward older samples.

METHODS

We calculated volumes of valley-bottom fill by interpolating between deposit cross sections in two adjacent reaches of approximately equal length but different network structure, gradient, and contributing area (Lancaster and Grant, 2006; Table 1; Fig. 1). We surveyed the longitudinal channel profile at a precision sufficient to capture all debris-dam impoundments (Lancaster and Grant, 2006) and spaced valley cross sections at intervals of ~10 channel widths, or less if necessary for accurate volume calculation. We extrapolated valley side slopes of 84% (or 40°, a modal value for our field site) beneath deposits to the intersection with a projected bedrock channel bed. Recalculation with side slopes of 173% (60°, the steepest observed) provided an estimate of error due to side-slope variations. Where the bedrock thalweg was covered, we interpolated its elevation with a linear projection between the nearest upstream and downstream bedrock points (Lancaster et al., 2001).

Distributions of transit times (defined as the time elapsed between deposition and evacuation) and deposit ages are not generally equivalent (Eriksson, 1971; Bolin and Rodhe, 1973; Dietrich et al., 1982). Ages of sediment exposed in channel banks may not be representative of valley-fill deposit ages. We reason that bank exposures are, however, representative of recently and soon-to-be evacuated sediments because these banks will be eroded within times that are small fractions of deposit age. Assuming steady-state storage volumes and statistical distributions—reasonable given modest variations in fire frequency in the past 9 k.y. (3–10 events/k.y.; Long et al., 1998) and the high frequency of debris-flow deposition events at this and similar sites in the Oregon Coast Range (also 3–10 events/k.y.; May and Gresswell, 2004)—it follows that bank ages can be interpreted as proxies for transit times, and large numbers of bank ages therefore allow estimation of transit time distributions. These distributions (e.g., Bolin and Rodhe, 1973; Malmon et al., 2003) are commonly right-skewed, have maximum likelihood at zero time, and are characterized by the mean. The mean is defined as the residence time, t_r, which is equal to the ratio of total mass or volume, M_0, to flux, F_0, through the fill (Eriksson, 1971):

$$t_r = \frac{M_0}{F_0}. \tag{1}$$

Using equation 1, we calculated mass fluxes (M_0) and percentages of basin-wide denudation passing through valley-bottom storage in the two reaches. We used residence times and deposit volumes measured at the Bear Creek site. From nearby similar sites, we used values of deposit bulk density (20 samples, mean 1.26×10^3 kg/m^3, range 0.86–1.91 × 10^3 kg/m^3; Lancaster, unpublished data, 2006), bedrock lowering rate (1.17×10^{-4} m/yr; Heimsath et al., 2001), and rock density (2.27×10^3 kg/m^3; Anderson et al., 2002).

Sampling of banks was random and weighted by local volume. Random, uniformly distributed coordinates were generated within the valley fill in three dimensions: (1) distance downstream, restricted to surveyed cross sections; (2) height above sediment-bedrock interface; and (3) distance from the valley wall. For actual sampling, right or left bank locations (with equal probability) were substituted for distance from the valley wall. Except where deposit ages were inferred from surface vegetation (or lack thereof) or lower samples in the same massive unit, datable materials were sampled from every location (Fig. 2; see the GSA Data Repository[1] for sampling details). Age estimates were not adjusted to account for the likely effect of trees' longevity (<600 yr; Gavin, 2001), but inferences based on individual samples were limited.

We interpreted the stratigraphy of the highest cut bank at each valley cross section, dividing into deposits from debris flows, coarse-grained fluvial deposition (fluvial gravels), or fine-grained fluvial deposition (fluvial fine). Debris-flow deposits lack imbrication or sorting and commonly have matrix-supported clasts (angular or rounded). Fluvial gravel deposits are imbricated, clast supported, and often stratified. Fluvial-fine deposits have fine grain sizes (sand and smaller) and are stratified.

RESULTS

Banks in the upper reach are largely composed of recent (younger than 500 ^{14}C yr B.P.) debris-flow deposits (>70% of samples). These have storage peaks at 1540 m, 1710 m, 1880 m, and 2030 m (Fig. 1). Deposits comprise sediments impounded by existing debris dams or relict terraces left behind after dam breaching. Only one of the samples is a fluvial deposit, which is impounded by a debris jam at 1540 m from the outlet. Recent debris flows have traversed and scoured the mainstem at 1820–1900 m and 2090–2540 m. The debris-flow–fluvial transition calculated according to Stock and Dietrich (2003) is at 1660 m from the outlet (Fig. 1).

The volume of valley fill is greater in the lower reach (Table 1), where 67% of sampled bank exposures are fluvial (37% coarse, 30% fine) and 33% are debris-flow deposits. All debris-flow deposits in the lower reach occur at tributary junctions (e.g., debris fans), indicating that debris flows do not commonly enter the lower reach along the mainstem. Tributary debris fans typically impound and even override fluvial deposits (Fig. 2). Recalculation of volumes assuming greater side slopes (173% versus 84%) increased the total by 8%, a reasonable estimate of uncertainty of volume measurements.

TABLE 1. CHARACTERISTICS OF SEDIMENT RESERVOIRS

Sediment reservoir	Lower basin	Upper basin	Full basin*
Contributing area (km^2)	2.23 (0.88)†	1.35	2.23
Gradient	2.5%–5%	5%–25%	N.A.
Volume (m^3)§	4.72×10^4	2.23×10^4	6.95×10^4
Mean sample age (residence time ^{14}C yr)	1.22×10^3	4.43×10^2	9.96×10^2
Standard deviation (^{14}C yr)	1.26×10^3	8.19×10^2	1.12×10^3
Median sample age (^{14}C yr)	6.38×10^2	1.68×10^2	N.A.
90th percentile of sample ages (^{14}C yr)	2.96×10^3	1.17×10^3	N.A.
Mass flux through reservoir (kg/^{14}C yr)#	4.87×10^4	6.34×10^4	8.79×10^4
Percent denudation entering storage**	12.4 (8.21–20.8)††	17.7	14.8

*Volume-weighted averages where appropriate, N.A. where not.

†Value in parentheses is local area, full basin (total) area minus upper basin area.

§Relative uncertainty, based on recalculation with side-slopes of 173%, is ± 8%.

#Assumes deposit bulk density of 1.26×10^3 kg/m^3 (Lancaster, unpublished data, 2006).

**Assumes bedrock lowering rate of 1.17×10^{-4} m/yr (Heimsath et al., 2001) in the upstream contributing area and (weathered) bedrock density of 2.27×10^3 kg/m^3 (Anderson et al., 2002) for a unit mass flux of 2.66×10^{-1} kg/m^2/yr.

††Assumes local contribution to storage is 59.4% and comprises fluvial deposits in proportion to ratio of local to total area and all debris-flow deposits; in parentheses, lower value assumes local contribution is 39.5%, the ratio of local to total area, upper end assumes local contribution is 100%.

[1]GSA Data Repository item 2007251, details of radiocarbon sampling and results, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

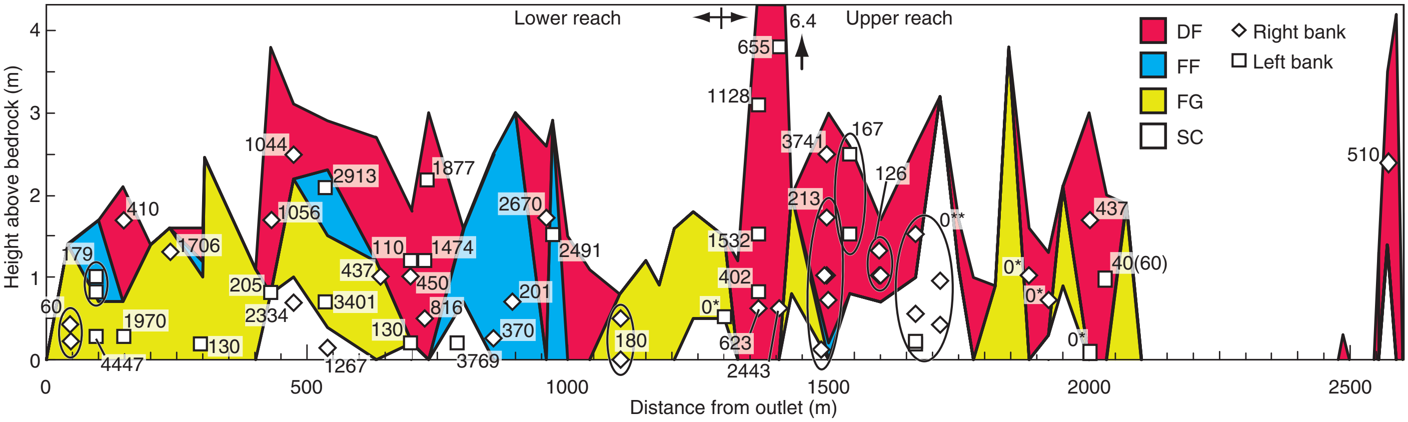

Figure 2. Cut-bank height at surveyed cross sections versus distance from outlet. Colors indicate deposit type: DF—debris flows; FF—fluvial fine; FG—fluvial gravels; SC— sediment covering bedrock (depth inferred). Interpolation between points is for illustrative purposes only: stratigraphic units are too numerous and localized to show legibly. Deposit ^{14}C ages (and 1σ errors where ≥50 ^{14}C yr) are shown as right bank (diamonds) and left bank (squares). In all cases, actual samples for ^{14}C dating were found within 2 m streamwise, 0.1 m vertical, and 0.5 m (excavated) lateral distance, respectively, of target locations, and were classified as detrital wood, detrital charcoal, wood, branch wood, streamlined branch wood (knots left by erosion of surrounding, softer wood), or wood bark. For detrital wood and charcoal, some samples comprised two or more small pieces. Encircled sampling points indicate where ages of higher samples were inferred from lower samples. Points with 0* have post–A.D. 1950 ^{14}C ages; points with 0 were not actually sampled, but all are within deposit inferred to date to A.D. 1996. All other points within SC were accessed by excavating bank-adjacent bed material. Failure of the law of superposition at (1) 727 m from the outlet may reflect old-wood deposition (Gavin, 2001); (2) 1365 m from the outlet is due to a bank collapse; and (3) 1496 m from the outlet is likely due to debris-flow entrainment and redeposition of older upstream fluvial deposits. For precise sample locations, characteristics, and age estimates, see the GSA Data Repository (see footnote 1).**

Transit time distributions inferred from bank ages exhibit large positive skew in both reaches, but the ^{14}C age exceedance probabilities reveal important differences (Fig. 3). An exponential distribution describes the lower reach data well: it explains much of the variance, the sample mean ^{14}C age is similar to the distribution's mean, and the sample mean and standard deviation are nearly identical (Table 1; Fig. 3). The upper reach data are inconsistent with an exponential distribution: it explains a smaller percentage of the variance, the distribution and sample means are dissimilar, and the sample standard deviation is nearly twice the sample mean (Table 1; Fig. 3). Most of the upper reach data are best fit by a power law (Fig. 3), $A\tau^{-b}$, where τ is ^{14}C age and $b < 2$, with undefined mean and higher moments (Fig. 3). Relatively small fractions of basin-wide denudation enter valley-floor storage (Table 1).

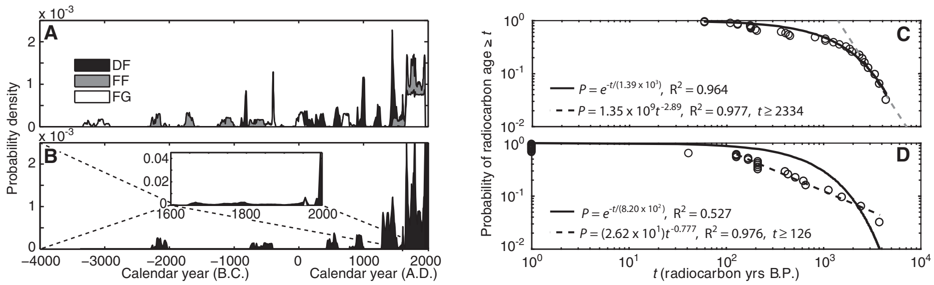

Figure 3. A, B: Normalized probability densities versus time (calibrated calendar dates from IntCal04 of Reimer et al. [2004a] and Bomb04NH1 of Hua and Barbetti [2004] for ^{14}C ages >0 and F14C >1, respectively; cf. Reimer et al. [2004b]) for samples from lower (A) and upper (B) reaches of Bear Creek. Shading indicates different facies contributions: black is debris flow (DF); gray is fluvial fine (FF); and white is fluvial gravels (FG). Inset in B shows detail of post–A.D. 1600 probability densities with expanded time axis and compressed probability axis. C, D: Exceedance probability (*P*) versus ^{14}C age (*t*, ^{14}C yr B.P.) for samples from lower (C) and upper (D) reaches of Bear Creek. Open circles are sample ages. Solid black lines are exponential distributions fit to all of the data, and dashed lines are power laws fit to the greater-age "tails" (equations shown with R^2, fraction of variance explained). In C, gray dashed lines show extrapolations beyond the data used in the power-law fit.

DISCUSSION

According to the estimated transit time distributions, half or more of headwater valley fill evacuates in times similar to the effective resolution, limited by tree age, of ^{14}C dating (600 ^{14}C yr; Gavin, 2001), but significant volumes remain for millennia. In the lower reach, where fluvial evacuation dominates, it takes 2.5 times longer to evacuate 90% of the sediment (T_{90} of Malmon et al., 2003) than in the upper reach, where debris flows dominate (Table 1).

In the special case of an exponential distribution (well-mixed case in reservoir theory), age and transit time distributions are identical (Eriksson, 1971; Dietrich et al., 1982), as are the means, and bank samples are an unbiased sampling of deposit ages. This case appears applicable to the lower reach and implies that all sediments are equally likely to be evacuated at any given time (Bolin and Rodhe, 1973). A non-exponential transit time distribution implies age-dependent evacuation probabilities. The power-law distribution, with its greater values at both short and long times, implies that most deposits are quickly evacuated (e.g., scoured by debris flows), but deposits that remain are preferentially preserved such that the mean age of valley-floor deposits is greater than the mean transit time, or residence time (Bolin and Rodhe, 1973).

Most of Bear Creek's annual sediment load bypasses storage on the valley floor, but 15% does not. Much of the stored material is coarse (≤80% by volume) and likely evacuated as bedload. In another basin of similar size and lithology in the Oregon Coast Range (Flynn Creek, 2 km^2, Tyee Formation), bedload is only 3% of sediment yield (Larson and Sidle, 1980). Much of the gravel eventually delivered to fish-bearing reaches spends a basin-wide average of ~1 k.y. in storage within the valley floor (Table 1).

CONCLUSIONS

Events that deposit sediment in the two headwater valley reaches have legacies that extend for millennia. Different combinations of deposition and evacuation mechanisms in the upper and lower reaches are reflected in transit times with different sample means and best-fit distributions. Debris-flow deposition and evacuation in the upper reach produce a shorter residence time and a power-law fit to the distribution of transit times. Debris-flow and fluvial deposition and (presumably) fluvial evacuation in the lower reach produce a longer residence time and an exponential fit to the distribution of transit times. A small part (15%) of basin-wide denudation passes through these reservoirs but is likely a large part of the bedload necessary for downstream salmonid spawning beds; in Oregon Coast Range streams, bedrock is commonly exposed or only thinly mantled with gravel. On the one hand, these reservoirs substantially buffer downstream aquatic habitat from debris flows, e.g., following disturbance events such as fires and timber harvest (Swanson et al., 1981; Montgomery et al., 2000); on the other hand, sediments derived from such upland disturbances persist for long times in the channel and valley system.

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