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Correction of deposit ages for inherited ages of charcoal: implications for sediment dynamics inferred from random sampling of deposits on headwater valley floors

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ABSTRACT

Inherited age is defined herein as the difference between times of carbon fixation in a material and deposition of that material within sediments from which it is eventually sampled in order to estimate deposit age via radiocarbon dating. Inheritance generally leads to over-estimation of the age by an unknown amount and therefore represents unquantified bias and uncertainty that could potentially lead to erroneous inferences. Inherited ages in charcoal are likely to be larger, and therefore detectable relative to analytic error, where forests are dominated by longer-lived trees, material is stored for longer periods upslope, and downstream post-fire delivery of that material is dominated by mass movements, such as in the near-coastal mountains of northwestern North America. Inherited age distribution functions were estimated from radiocarbon dating of 126 charcoal pieces from 14 stream-bank exposures of debris-flow deposits, fluvial fines, and fluvial gravels along a headwater stream in the southern Oregon Coast Range, USA. In the region, these 3 facies are representative of the nearly continuous coalescing fan-fill complexes blanketing valley floors of headwater streams where the dominant transport mechanism shifts from debris-flow to fluvial. Within each depositional unit, and for each charcoal piece within that unit, convolution of the calibrated age distribution with that of the youngest piece yielded an inherited age distribution for the unit. Fits to the normalized sums of inherited age distributions for units of like facies provided estimates of facies-specific inherited age distribution functions. Finally, convolution of these distribution functions with calibrated deposit age distributions yielded corrections to published valley-floor deposit ages and residence time distributions from nearby similar sites. Residence time distributions were inferred from the normalized sums of distributions of ~30 deposit ages at each of 4 sites: 2 adjacent valley reaches ~10^3 m long and within ~10^2 m of 2 tributary confluences. Mean inherited ages from the observed distributions are 666, 688, and 1506 yr for debris-flow deposits, fluvial fines, and fluvial gravels, respectively. On average, correction reduced estimates of individual deposit age means by a factor of 0.71 (0.56–0.94) and increased standard deviations by a factor of 6.1 (0.97–43). Across sites, mean residence times decreased by 24.0% and standard deviations by 12.5% on average. Corrected residence time distributions have thicker tails, as indicated by gamma-distribution fits with smaller shape factors, and these changes are significant relative to the bootstrapped 95% confidence limits representing potential error in the sampling for inherited ages. The ratio of the means of sediment age and residence time ranged from 1.03 to 1.80 across sites before correction and 1.21 to 2.18 after correction, where a value of one implies that probability of evacuation from the "reservoir" comprising valley-floor deposits is independent of time since deposition. Corrected values of this ratio therefore indicate that evacuation favors younger deposits at all sites, whereas uncorrected results implied age-independent evacuation from the more downstream valley reach.

1. Introduction

Radiocarbon dating of organic material is often used to estimate the age of the sediment deposits in which the material is found

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(e.g., Personius et al., 1993; Bush and Stillman, 2007; Pierce and Meyer, 2008), but an accurate estimate based solely on radiocarbon dating assumes that the dated material was young, i.e., had effectively zero age, at the time of deposition. Two kinds of cases violate this assumption: 1) the material was not incorporated into a deposit shortly after carbon fixation; and 2) the material remained, for an extended period of time, in storage on its journey from its source to a particular deposit (e.g., Blong and Gillespie, 1978).

In radiocarbon dating, and consistently herein, age is effectively treated as a random variable, T, with a probability density function (PDF), $f_T(t)$, that incorporates uncertainties in both radiocarbon concentration in the dated material and the calibration curve relating radiocarbon concentration to calendar age. The expected value of age is the mean, $\overline{T} = \int_{-\infty}^{\infty}[tf_T(t)]\mathrm{d}t$, sometimes called the "weighted mean," where the PDF is the weighting function (Telford et al., 2004). Uncertainty is expressed in terms of the standard deviation, or the square-root of the variance, $\sigma_T^2 = \int_{-\infty}^{\infty}[(t-\overline{T})^2 f_T(t)]\mathrm{d}t$. In this paper, we explicitly incorporate uncertainties due to violations of the zero-age assumption and determine whether these uncertainties significantly affect, on the one hand, age estimates and uncertainties associated with individual samples of organic material and, on the other hand, inferences of system behavior (in this case, geomorphic) based on many samples.

Some definitions are necessary to draw distinctions among the various "ages" and "times" considered herein. "Sample age" is the time between carbon fixation within and radiocarbon dating of a sample of organic material, typically charcoal or wood. "Deposit age" is the time since deposition of the sediment in a unit or stratum from which a sample is taken for radiocarbon dating. "Inherited age" is the time between carbon fixation within a sample and its deposition within the unit to be dated and is equivalent, at least conceptually, to the difference between sample age and deposit age. Inherited age includes "inbuilt age," which Gavin (2001) defined as the time between carbon fixation and charcoal formation. Geomorphologists have used deposit ages, e.g., of bank exposures, to infer sediment residence times, where "sediment residence time," or simply "residence time," is the time between deposition and evacuation of sediment and is also known as "transit time" or "storage time." System characteristics determine the residence time distribution and its moments (e.g., mean, variance), and to a limited extent, vice versa. In particular, the residence time distribution implies the distribution of "sediment age." Like deposit age, sediment age is defined as the time since deposition but is used here in the context of a probability distribution for all sediments within a "reservoir," i.e., a control volume in which sediment may be stored, such as an alluvial fan. Similarly, residence time is used in the context of sediments leaving a reservoir (Eriksson, 1971; Bolin and Rodhe, 1973; Dietrich et al., 1982; Lancaster and Casebeer, 2007; Lancaster et al., 2010; Bradley and Tucker, 2013).

After Aubry et al. (2009), we report durations with the unit of "year," or "yr" (or "kyr" for "thousands of years") and dates relative to the present with the unit of "annus," or "a" (or "ka" for "thousands of years before present"). Sample ages are reported as dates in calibrated or radiocarbon years relative to AD 1950 ("a BP" or "^{14}C a BP," respectively). Deposit ages, inherited ages, residence times, and sediment ages are reported as durations. Inherited ages require no reference datum, but the others are inferred from ages relative to the time of sampling.

Magnitudes of inherited ages and, thus, the biases inherent in many deposit age estimates are generally unknown and therefore not systematically accounted for. Blong and Gillespie (1978) found inherited ages of bulk charcoal samples from a river bed in coastal New South Wales as great as 1500 ^{14}C yr and therefore regarded any single sample age as a "maximum" deposit age, i.e., an age estimate that may be larger than the actual age by an unknown amount. Stratigraphic age control can constrain these magnitudes, essentially revealing cases in which inherited ages are large enough to cause age inversions (i.e., stratigraphically higher samples yielding greater ages than lower samples). For example, in 7 sites with stratigraphic age control, Lancaster and Casebeer (2007) and Lancaster et al. (2010) found 3 age inversions of 455, 976, and 3909 yr in headwater valleys of the Oregon Coast Range. Dating of multiple samples and assuming that the actual deposit age is equal to the minimum of the sample ages can reduce error, but again, that error is not well described (e.g., Tornqvist et al., 1992; Meyer et al., 1995; Akciz et al., 2009). Moreover, the necessary number of samples may make this method impractically large. Based on differences between timing of fire events inferred from dating of soil charcoal and counts of tree rings on the west side of Vancouver Island, Gavin (2001) found that only 3 of 26 samples had inbuilt ages less than 150 yr, whereas the median and maximum were 270 yr and 670 yr, respectively. Gavin et al. (2003) incorporated this uncertainty by a convolution of the distribution of inbuilt ages with calibrated age distributions, but his method required independent determination of the true times of the types of events in question, information that may be unobtainable in many cases, such as with the timing of ordinary fluvial deposition.

The events leading to charcoal deposition in valley-floor sampling sites may form lengthy histories: After radiocarbon is fixed in new woody material by organisms (i.e., trees), those organisms may live for many years before dying, and that death may precede burning and, hence, charcoal production by additional years. Moreover, decay may expose older interior wood, which may then be susceptible to burning during fires (Gavin, 2001). Charcoal may then remain on dead tree trunks for some time before falling, after which the charcoal on hillslopes may be incorporated into mobile regolith, which will, after some time, work its way downslope and into areas prone to erosion by overland flow or mass movement, where that charcoal may remain for many years before moving downslope with eroded sediment, often via debris flow, and into channel networks. Charcoal pieces may then stay in one or more valley-floor deposits for many years before finally coming to rest in the fluvial or debris-flow deposits from which we take samples for radiocarbon dating (Nichols et al., 2000). Or, the times between these effectively stochastic events may be short enough that inherited ages are negligibly short.

In the absence of appropriate site-specific data, uncertainty with respect to deposit ages is nearly unbounded. For example, Lancaster et al. (2010) found charcoal samples with mean calibrated ages of 16.6 ka BP, 148 a BP, and 168 a BP, from bottom to top, in an otherwise unremarkable stream bank in the Oregon Coast Range. The upper samples provide effectively no constraint on the inherited age of the lowest.

The accuracy of statistics assembled from many samples may be more important than, but just as uncertain as, the accuracy of any one deposit age. For example, using reservoir theory and large numbers of ages of deposits exposed in stream banks as proxies for residence times, Lancaster and Casebeer (2007) and Lancaster et al. (2010) inferred sediment flux rates and relative probabilities of valley-floor sediment evacuation as a function of sediment age. According to reservoir theory, if residence times are exponentially distributed, mean residence times are equivalent to mean sediment ages, and evacuation probability is invariant with respect to sediment age. In contrast, if residence time probabilities decrease more slowly with time (i.e., have thicker tails) than an exponential distribution, then mean residence times are less than mean sediment ages for the entire reservoir, and evacuation probability decreases with sediment age (Eriksson, 1971; Bolin and Rodhe, 1973; Dietrich