Explicit treatment of inheritance in dating depositional surfaces using in situ ^{10}Be and ^{26}Al

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ABSTRACT

We describe a new strategy for dating depositional landscape surfaces using in situ–produced cosmogenic radionuclides (CRNs) that removes the complication of nuclide inheritance by clasts prior to deposition. Two amalgamated samples, each consisting of 30 clasts, one from the surface and one from a fixed depth in the subsurface, constrain this CRN inheritance and date the surface. The inheritance may be used to estimate minimum exhumation rates and maximum transport times within the geomorphic system. We test the technique using ^{10}Be and ^{26}Al to date the third (FR3) of five terraces along the Fremont River, Utah, and the third (WR3) of 15 along the Wind River, Wyoming. Whereas effective ages based solely upon the surface samples yield 118–138 ka (FR3) and 93 ka (WR3), the subsurface samples reveal that inheritance accounts for 22% (WR3) to 43% (FR3) of the total CRN concentration. Taking this into account yields terrace ages of ~61–81 ka for FR3 and ~67–76 ka for WR3. We explore the dependence of age estimates on the accumulation history of the terrace silt caps.

INTRODUCTION

Dating of depositional surfaces, such as fluvial and beach terraces, alluvial fans, and moraines, is necessary for constraining rates of tectonic uplift, river incision, and pedogenic evolution, and for establishing links between oceanic and terrestrial records of climate change. However, dating of these landforms currently relies on methods with significant temporal, geographic, or lithologic limitations. We explore a method that employs in situ–produced cosmogenic radionuclide (CRN) concentrations to estimate the residence time of clastic material on the depositional surface. These surfaces often contain good target material for the production of CRNs, and several commonly used CRNs have half-lives that allow use through the Quaternary. Whereas in situ CRN studies using ^{10}Be, ^{26}Al, and ^{36}Cl have focused largely on dating of erosional bedrock surfaces (Lal, 1991; Nishiizumi et al., 1993; Bierman, 1994; Cerling and Craig, 1994), Phillips et al. (1990) and Chadwick et al. (1994) have dated moraines and outwash terraces, and Trull et al. (1995) have attempted to date shorelines.

Although many potential problems have been addressed by previous workers, especially in dealing with dynamic landforms (Bierman, 1994; Hallet and Putkonen, 1994), inheritance during exhumation and transport places an additional limitation on the application of in situ–produced CRNs to the dating of depositional surfaces. The clasts within most deposits have undergone not only CRN production at the final site of deposition, but also potentially significant and highly variable production throughout their path to this site (Fig. 1). Dating of a single surface clast by CRN methods reveals at best only a maximum age of the surface, leading Cerling and Craig (1994, p. 310) to state that "in the end such studies will require numerous samples to overcome the stochastic nature of sediment transport and surface residence history."

Measurement of many clasts, taking the minimum effective age to be that of the surface, is expensive in both time and funds, and may still result in the wrong answer. As a more robust and economical alternative, we present a method in which many individual clasts are amalgamated to construct two samples, one from the surface and one from the subsurface, that explicitly addresses the issue of CRN inheritance and allows strong constraints to be placed on both the surface age and the transport history of clasts within the geomorphic system.

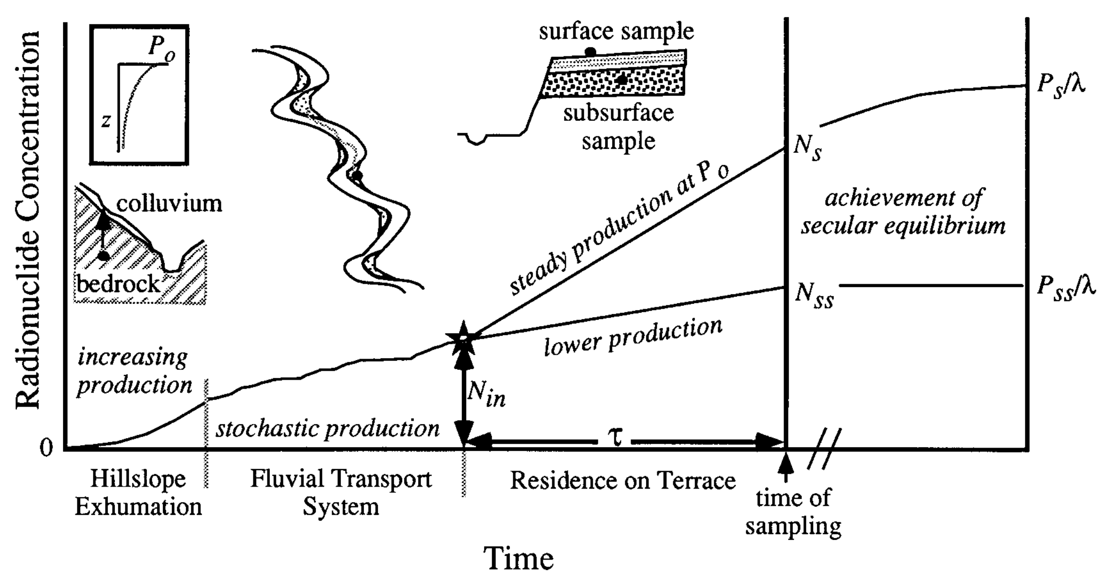

Figure 1. Cosmogenic radionuclide concentration history of clast through its transport history in hillslope and fluvial systems, and in its subsequent residence on depositional site. Production rate is dictated by depth beneath local surface, *z*, which falls off exponentially with depth (inset). Exhumation on hillslope results in monotonic increase in concentration. Production history is stochastic within fluvial system, as clast travels between point bars, within which it is buried to differing depths. Evolution of concentration on final terrace site is shown for two possible burial depths, one on surface, other in subsurface. One scenario for surface clast (see Fig. 3 for others) is that it remains on silt surface, in which case it always sees surface production rate P_o, and attains sampled concentration of N_s. Subsurface clast within underlying gravels (stippled) will undergo lower production rate, and is sampled with concentration N_{ss}. Clasts on terraces much older than nuclide half lives attain secular equilibrium, with labeled concentrations. Amalgamated samples consisting of numerous clasts allow back-calculation of terrace age, τ, and of mean inherited radionuclide concentration, N_{in}.

METHOD OF CONSTRAINING INHERITANCE

We focus on the radionuclides ^{10}Be and ^{26}Al, with half-lives ($t_{1/2}$) of 0.7 and 1.5 Ma, respectively, although the results are applicable to other stable and radionuclide systems. It is sufficient to know (1) that the in situ production rate of the nuclide at the surface, P_o, is dependent upon the altitude and latitude in a way that has been well constrained (Lal, 1991), and (2) that the production rate, P, falls off exponentially with depth, z, with a characteristic length scale z^* ($=\Lambda/\rho$, where Λ is the mass attenuation coefficient, and ρ is the bulk density of the near-surface material; Lal, 1991; Nishiizumi, 1994); i.e., $P = P_o \exp(-z/z^*)$. Because $z^* \approx 0.6$ and 0.8 m in rock and alluvium, respectively, it is the clast residence time and depth trajectory within roughly 1 m of the surface during exhumation and transport that results in nuclide inheritance.

A clast may accumulate CRNs that contribute to the inherited signal throughout its history. The final CRN concentration, N, in a clast from a depositional surface is

$$N = N_{pre} + N_{exh} + N_{trans} + N_{dep} = N_{in} + N_{dep}, \tag{1}$$

where N_{pre} is the concentration retained from an ancient transport-depositional cycle; N_{exh} is the concentration produced during exhumation; N_{trans} is that produced during transport to the final depositional surface; and N_{dep} is that produced during residence on the final depositional surface. The first three terms correspond to inheritance, N_{in}. All terms must include radioactive decay.

Consider the history of an individual clast. During exhumation, the clast spends time within the zone of cosmic ray penetration; the resulting production of CRNs yields N_{exh} upon arrival at the ground surface (Fig. 1), which depends upon the time it takes to pass through the zone of cosmogenic production. Ignoring small changes in altitude that take place during exhumation through the CRN production zone, assuming that erosion is steady, yields (Lal, 1991):

$$N_{exh} = \frac{P_o}{\lambda + \dot{\epsilon}/z^*}, \tag{2}$$

where $\lambda = \ln 2/t_{1/2}$ is the nuclide decay constant.

Once the clast is free to move, processes ranging from glacial and fluvial transport to longshore drift move it through the geomorphic system. The clast undergoes periods of storage at varying depths within the geomorphic system, introducing a stochastic component to the production history (Fig. 1). Consider $z(t)$, the depth history of the clast during transport, to be a random function over the range $[0, H]$, where 0 represents the surface, and H the maximum possible burial depth within the transport system. Integrating the accumulation history using the simplest case of uniform probability between $z = 0$ and H yields

$$N_{trans} = P_o T \left\{ \frac{1 - e^{-(H/z^*)}}{(H/z^*)} \right\}, \tag{3}$$

where T is total time spent in the fluvial system (both in transport and in storage). For H greater than a few times z^*, this reduces to the yet simpler expression $N_{trans} = (P_o\, T\, z^*)/H$. The combination Tz^*/H represents the effective time spent by the clast in the production zone. For large H, the clast spends less time close to the surface and accumulates fewer CRNs. Given that variations in z^* are expected to be small within such fluvial deposits (<10%), the clast-to-clast variation in N_{trans} arises principally from variations in total time in the fluvial system, T.

Following transport, a clast comes to rest within the deposit we wish to date. Because of the stochastic nature of exhumation and transport, any two clasts within the deposit are likely to have different CRN concentrations, resulting in unknown error when dating the surface using single clasts. However, measurement of a large collection of clasts should constrain the mean inheritance, $\overline{N_{in}}$. The average CRN concentration of many clasts immediately after deposition represents a combination of the mean hillslope exhumation rate $\langle\dot{\epsilon}\rangle$ and transport time, $\langle T\rangle$, undergone by the population of clasts. If $\overline{N_{in}}$ does not vary with position on or depth within the deposit, and if the clasts were deposited over a period short relative to the deposit age, then we may use the following strategy to account for inheritance and constrain the deposit age.

Subsequent to final deposition, accumulation of radionuclides depends only upon the depth of the clast and the bulk density of the overlying deposit (Fig. 2). We first measure the cosmogenic radionuclide concentration, N_s, of an "amalgamated sample" created by combining equal masses from many surface clasts (depth $z = 0$; production rate $P_s = P_o$). This concentration is the sum of the mean of the stochastic inherited component, $\overline{N_{in}}$, and that acquired during residence on the depositional surface, N_{dep}. Second, we measure the CRN concentration, N_{ss}, from a similarly amalgamated sample derived from many clasts collected from a known depth in the subsurface, z_{ss}. If there is no vertical variation in $\overline{N_{in}}$, the contribution from inheritance should be similar between the surface and subsurface amalgamated samples. However, the postdepositional production rate in the subsurface sample should be reduced below that of the surface sample (Fig. 2). We therefore use the CRN production rates for each sample depth to back calculate both the time at which the samples had similar CRN concentrations (the surface age, τ), and the magnitude of this concentration (the CRN inheritance, $\overline{N_{in}}$). Graphically, this is analogous to tracing back the CRN trajectories from their measured values, N_s and N_{ss}, along lines inclined at P_o for the surface sample and at $P_o \exp(-z_{ss}/z^*)$ for the subsurface sample until they intersect (star in Fig. 1). For the case in which we may safely assume no radioactive decay (stable nuclides, or surface age young relative to the nuclide half-life), this intersection occurs at $\tau = \Delta N/\Delta P$, where $\Delta P = P_s - P_{ss}$, and $\Delta N = N_s - N_{ss}$. Taking into account decay,

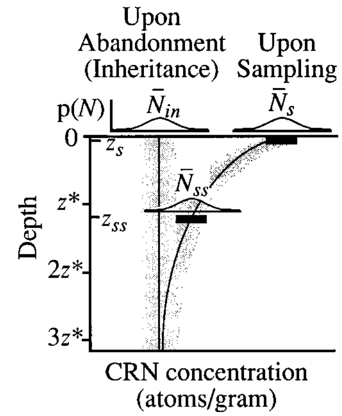

Figure 2. Schematic illustration of postdepositional accumulation of cosmogenic radionuclides. (CRNs) at various depths. Terrace gravels mantling strath surface cut into bedrock arrive on site with varying cosmogenic inheritance (wide fuzzy line), but are assumed to have been emplaced with uniform distribution of CRN inheritance with depth, characterized by mean, $\overline{N_{in}}$, and spread represented by fuzzy line and shape of probability density, p(N). Subsequent accumulation of CRNs results in exponentially decaying component, altering mean of distribution, but not spread (curved fuzzy line). Mean concentrations derived from amalgamating samples (black boxes) from surface (z = 0) and subsurface (z = z_{ss}) will differ from one another only by this postdepositional component. Both initial uniform inheritance, $\overline{N_{in}}$, and elapsed time since abandonment of surface can be calculated from measured CRN concentrations of amalgamated samples.

TABLE 1. COSMOGENIC RADIONUCLIDE ANALYSES FROM FREMONT AND WIND RIVER TERRACES

Location	Sample	Altitude (m)	Latitude (°)	Depth (m)	θ (°)	number of clasts	P(Be) *	N(Be)+ (x10^6)	T_{eff} Be (ka) §	P(Al) *	N(Al)+ (x 10^6)	T_{eff} Al (ka) §	T_{adj} (ka)	N_{in}+ (x 10^6)	H/z*	ξ (μm/yr)	T_{trans} (ka)
FR3																	
single	7252-11a	1460	38.3	0	4	1	17.5	2.12	125	106	12.8	129					
single	7253-12a	1455	38.3	0	5	1	17.5	2.47	146	106	14.5	148					
surface	3314-4B	1439	38.3	0	0	32	16.6	1.90	118	100.4	13.0	138	61 Be	0.90 Be	10	11	548
subsurface	3314-5B	1433	38.3	1.75	0	25	1.6	1.00		10.9	5.96		81 Al	5.08 Al			
WR3																	
surface	92894-3	1700	43.4	0	0	29	22.7	2.12	95.5	136.1	12.6	97.1	67.3 Be	0.59 Be	10	23	260
subsurface	92894-1,2	1700	43.4	1.4	0	28	3.0	0.797		16.9	3.58		76.3 Al	2.22 Al			

* Atoms/gram quartz per year, taking into account latitude, altitude, depth and exposure geometry, θ.

§ Effective surface age taking into account decay.

+ Atoms/gram quartz.

$$\tau = \frac{1}{\lambda} \ln \left(\frac{\Delta P}{\Delta P - \lambda \Delta N} \right). \quad (4)$$

The inheritance can then be calculated: $\overline{N_{in}} = N_{ss} - P_{ss}\tau = N_s - P_s\tau$.

Application of this strategy requires estimation of the number of clasts needed to establish $\overline{N_{in}}$ in the amalgamated samples. Numerical modeling using plausible exhumation and transport scenarios suggests that 30 clasts are sufficient to constrain the mean to within 5% (Repka et al., 1994).

APPLICATIONS IN FLUVIAL SYSTEMS

We have tested this technique on fluvial strath terraces in the western United States. Along the Fremont River in Utah, terrace ages have been estimated (Howard, 1970, 1986) through correlation with glacial moraines upstream thought to correlate with the Pinedale and Bull Lake moraine chronology (Flint and Denny, 1956); no absolute ages exist. On the Wind River terraces in Wyoming, the date of one terrace (WR3) was determined by application of ^{36}Cl (Chadwick et al., 1994), although inheritance was not considered.

At both sites, we use quartzite clasts for ^{10}Be and ^{26}Al because: (1) SiO_2 is an ideal target for production of both nuclides (Nishiizumi et al., 1993), and quartzites are close to being pure SiO_2; (2) quartzite is very resistant to weathering, and thus interpretation is not complicated by postdepositional erosion of the clast (Phillips et al., 1990; Chadwick et al., 1994); and (3) the quartzites are derived from formations whose ages are several orders of magnitude greater than the half-lives of either nuclide, so that N_{pre} is safely neglected.

In the field, we document the latitude and elevation of the sample, from which the flat-surface production rate is calculated (e.g., Lal, 1991), and measure the angle to the horizon, θ, in eight directions in order to calculate the topographic shielding factor (Lal, 1991; Cerling and Craig, 1994). Subsurface sampling depth and thickness of the silt cap are noted. In the lab, ~30 clasts are crushed and sieved individually to a uniform size of 200–500 μm, and an equal mass is removed from each to create an amalgamated sample. Organic coatings, Fe and Mg oxides, and carbonate coatings are eliminated with weak acids, after which the samples are subjected to a series of leaches to remove non-quartz silicates (Kohl and Nishiizumi, 1992) and to eliminate "garden variety" ^{10}Be. Subsequent total dissolution, ion chromatography, and accelerator mass spectrometry (Elmore and Phillips, 1987; Davis et al., 1990) are standard.

FREMONT RIVER

Five well-expressed terraces of the Fremont River (FR1–FR5, from lowest to highest) are constructed of outwash from glaciers that bounded the Aquarius and Fish Lake plateaus to the west. Each terrace is a strath surface cut into the Mancos shale and sandstone bedrock, mantled by 3–5 m of coarse gravel and sand. All terrace surfaces display a single layer of varnished clasts capping a few centimetres of nearly clast-free silt.

The largest terrace-cover clasts (up to 1 m) are basalts; locally derived sandstone and more far-traveled quartzite and chalcedony clasts have maximum diameters of 20 cm. The quartzites are derived from the Triassic Shinarump conglomerate and the Jurassic Brushy Basin member of the Morrison Formation (Billingsly et al., 1987).

Results

^{26}Al and ^{10}Be results from the laterally extensive terrace FR3, 90 m above the floodplain, are in very good agreement for the single surface clast samples (Table 1). The spread of effective exposure ages ($T_{eff} = 1/\lambda \cdot ln[P_o/P_o - \lambda N_s]$ taking into account decay) estimated from single surface clasts on this and other terraces (Repka et al., 1994) is very large (e.g., 130 ka [n = 7] for FR2 and 25 ka [n = 3] for FR3), indicating that inheritance is indeed significant. Given the small number of single clasts analyzed, the true age spread of individual clasts is probably even greater. The terrace surfaces are at least as young as the youngest surface clasts. If inheritance were not taken into account, the amalgamated surface sample from FR3 would suggest that this terrace was abandoned at 118 ka (Be) or 138 ka (Al) (Table 1). Using the CRN concentration of our amalgamated subsurface sample, and employing equation 4, we both revise this age estimate downward to 61 ± 3 ka (Be) or 81 ± 3 ka (Al) (T_{adj} in Table 1) and estimate the inheritance, $\overline{N_{in}}$. Roughly 43% of the CRN concentration of the surface sample is apparently due to inheritance. At present we have no explanation for the discrepancy between ^{10}Be and ^{26}Al results on the amalgamated FR3 samples, and we will use the mean of the adjusted ages (~71 ka) in our discussion.

WIND RIVER

The Wind River drains the northeast flank of the Wind River Mountains and the southern flank of the Absaroka Mountains. Fifteen well-preserved terrace surfaces, numbered WR1 through WR15 from lowest (youngest) to highest (oldest), probably span the entire Pleistocene (Chadwick et al., 1994). The terraces are strath surfaces mantled with several metres of coarse alluvial gravel and capped by tens of centimetres of silt.

Using cosmogenic ^{36}Cl, Phillips and Zreda dated the WR3 surface (Chadwick et al., 1994). They sampled the crests of four large (several metres diameter) Precambrian metamorphic boulders on the terrace surface, which minimize postdepositional erosion by ventifaction and fire spall (e.g., Bierman and Gillespie, 1991; Zimmerman et al., 1994). Three of the boulders had exposure ages of ~115 ka, the other had an age of 290 ka. They concluded that the age of the surface is 115 ka, interpreting the 290 ka age to reflect a significant prior exposure history for that particular boulder. This places the terrace and associated moraine in isotope stage 5.

We collected quartzite cobbles (several to

20 cm in diameter) from the WR3 terrace roughly 65 km downstream of the site sampled by Phillips and Zreda (Chadwick et al., 1994). The surface clasts were collected from the top of the silt layer, and subsurface cobbles were collected from gravel exposed in soil pits (Table 1). Surface clasts did not display carbonate coatings. There is no evidence of bioturbation within the gravels; depositional imbrication is still intact, and carbonate coatings are confined to clast bases.

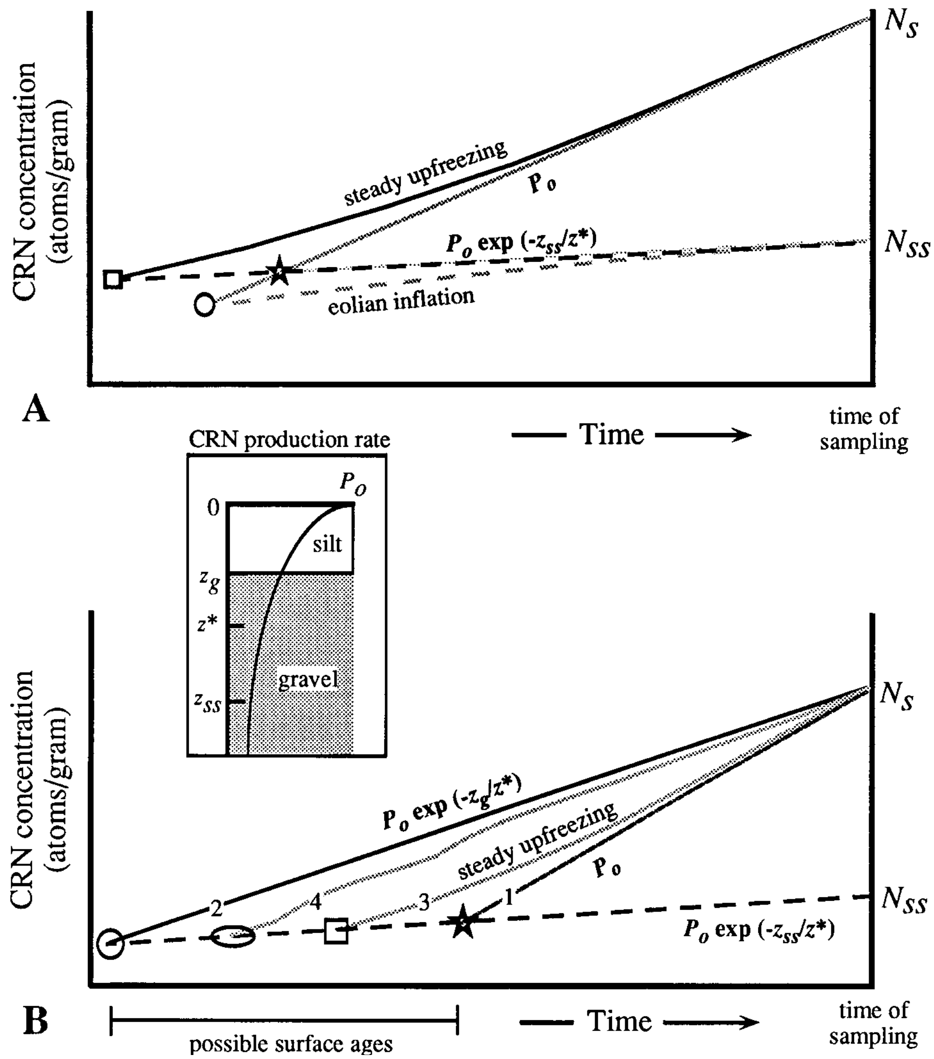

Figure 3. A: Cosmogenic radionuclide (CRN) histories for two possible postdepositional scenarios, resulting in identical measured CRN concentrations of surface and subsurface samples, N_s and N_{ss}. Time scales here are assumed to be short relative to decay times for these radionuclides. In first "eolian inflation" case (light lines, solid for surface sample, dashed for subsurface; circle depicts inherited concentration and time of surface abandonment), clasts sampled at surface have remained on surface throughout, riding upward on growing silt layer through desert pavement processes. Their production rate is always P_o, as denoted by slope of line. Eolian inflation progressively buries subsurface sample, reducing rate of production through time, reaching final value appropriate for its sampled depth, z_{ss} (see inset). In second "upfreezing" case (heavy lines; box depicts inherited concentration and time of surface abandonment), mantling silt is taken to be fluvial, and does not further inflate through time. CRN accumulation in subsurface sample is therefore steady, at rate $P_o \exp(-z_{ss}/z^*)$. Clasts sampled from surface are assumed to rise through silt layer, emerging at surface soon before sampling. They undergo increasing rates of production, eventually reaching rate P_o. Back projection of production histories using steady production rates appropriate for sampled depths intersect at star; in both cases, surface age is underestimated. B: Four possible postdepositional scenarios in which silt is rapidly accumulated and remains of steady thickness, all of which yield same measured surface and subsurface CRN concentrations, N_s and N_{ss}. CRN accumulation in subsurface sample is slow but steady (dashed line), at rate dictated by sample depth, z_{ss} (see inset). If gravels constituting surface sample remain on surface essentially since deposition (early upfreezing, or desert pavement), then CRN history of such a sample is depicted by line 1, whose slope is P_o, and estimated age (star) is youngest. Case in which gravels remained at gravel-silt interface until just prior to sampling (very late upfreezing), undergoing slowest possible production rate (line 2), yields oldest age estimate (circle). Steady upfreezing yields monotonically increasing production rate (line 3), while bioturbation and cryoturbation result in rates that fluctuate erratically from P_o to $P_o \exp(-z_g/z^*)$, z_g being depth of gravel-silt interface (line 4). These result in intermediate surface age estimates (square and oval).

Results

^{26}Al and ^{10}Be analyses of our surface amalgamated sample (Table 1) yield effective exposure ages of 97 ± 6 ka (Al) and 95 ± 5 ka (Be). These estimates are close to three of the four boulder ages reported in Chadwick et al. (1994). However, using the subsurface sample to correct the surface age for inheritance (equation 4) results in age estimates of 76 ± 8 ka (Al) and 67 ± 7 ka (Be). These estimates overlap at ~72 ka.

DISCUSSION

The downward revision of the age estimate required by the measured inheritance is dramatic. The FR3 age is revised downward to ~71 ka, potentially associating this terrace with isotope stage 4, and doubling the implied incision rate of the Fremont River. The WR3 age becomes ~72 ka, strongly supporting the inference, based upon morainal soil development, of a Wind River Mountains glaciation between the classic Pinedale and Bull Lake glaciations (Hall and Shroba, 1995).

These calculated terrace ages are dependent upon the accretion history of the silt cap, and the postdepositional vertical motion of clasts within it. In our initial calculation, we assumed that the silt was deposited very near the time of abandonment of the surface, and that the sampled surface clasts reached the surface (by whatever means) shortly thereafter and have remained on the surface. Several other scenarios must be entertained (Fig. 3). The rise of clasts through the silt may have taken substantially more time, perhaps through upfreezing under periglacial conditions (Anderson, 1988). On the other hand, the silt could be eolian, and the monolayer of clasts remains on the surface as a desert pavement during slow eolian accumulation (Wells et al., 1995). Both cases revise the postdepositional CRN production histories of clasts. Numerical model results (Repka et al., 1994) show that for the silt caps on these terraces the necessary correction due to the increasing depth of the subsurface sample is not large (order 5%), is not sensitive to the details of the inflation history, and always increases the estimated surface age (Fig. 3A). Our estimate of the WR3 age would rise at most from ~72 ka to ~77 ka.

Uncertainties in the vertical motion histories of clasts in the surface sample can significantly affect age estimates, however (Fig. 3B). Whereas subsurface gravels have not undergone relative movement (due to cryoturbation, bioturbation, upfreezing), this is not certain for the surface clasts. The greatest increase in the estimated age of the surface occurs if (1) the silt is deposited rapidly (either fluvially or by rapid postabandonment deposition of eolian silt), and (2) the clasts resided at the base of the silt until very recently (Fig. 3B). Sampled surface clasts then undergo the lowest possible mean postdepositional production rate. This increases our estimated terrace age for the WR3 terrace from 72 ka to 133 ka. Intermediate cases arise if the clasts are cycled through the silt via cryoturbation and bioturbation (Fig. 3B). On WR3, this would alter the age estimate to roughly 105 ka. Combinations of eolian silt accumulation and upfreezing that keep clasts near the surface reduce the correction considerably. For example, using a steady silt accumulation scenario, the oldest the WR3 terrace could be is 84 ka.

Although the lack of carbonate coatings on surface clasts argues against long residence in the subsurface, the wide range of possible surface clast production histories lowers our confidence in the calculated surface ages. Work in progress, in which numerous amalgamated samples are taken at depth within the gravels, is designed to distinguish among these silt scenarios, and to test the assumption that the gravels were rapidly deposited.

The measured mean CRN inheritance, $\overline{N_{in}}$, can constrain the transport times and hillslope exhumation rates (Table 1). If the measured inheritance in the FR3 (WR3) samples was acquired entirely during transport ($\overline{N_{in}} = N_{trans}$), inversion of equation 3, assuming $H/z^* = 10$, yields $\langle T \rangle = 548$ ka (260 ka) (Table 1). If instead the entire inheritance was acquired during exhumation ($\overline{N_{in}} = N_{exh}$), inversion of equation 2 implies $\dot{\epsilon} = 11$ μm/yr (23 μm/yr). Because inheritance is the sum of that obtained during each of these processes, we can only state that the calculated mean hillslope exhumation rates are minima, and the mean transport times are maxima. It is clear, however, that the two geomorphic delivery systems are distinctly different.

Our technique provides an important advance in the dating of depositional surfaces while raising a cautionary flag. The inheritance of CRNs is potentially significant and must be considered in estimating surface ages. Taking the youngest effective age of a few individual clasts to represent the age of a surface is risky; all clasts are likely to have inherited nuclides within the geomorphic system. The inheritance is not simply noise to be removed; it can be used to quantify long-term exhumation rates and transport times that are otherwise very difficult to constrain.

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