Short communication: Cosmogenic noble gas depletion in soils by wildfire heating

Greg Balco[1,2], Alan Hidy[1], William T. Struble[3], and Joshua J. Roering[4]

[1]Lawrence Livermore National Laboratory, PO Box 808, Livermore CA 94551 USA
[2]Berkeley Geochronology Center, 2455 Ridge Road, Berkeley CA 94709 USA
[3]Department of Geosciences, University of Arizona, Tucson AZ 85721 USA
[4]Department of Earth Sciences, University of Oregon, Eugene OR 97403 USA

Correspondence: Greg Balco (balco1@llnl.gov)

Abstract.

Measurements of cosmic-ray-produced beryllium-10, neon-21, and helium-3 in quartz in a soil profile from a forested landscape in the Oregon Coast Ranges show that the cosmogenic noble gases ^{21}Ne and ^{3}He are depleted relative to ^{10}Be in the shallow subsurface. The noble gases are mobile in mineral grains by thermally activated diffusion and ^{10}Be is not, implying that noble gas depletion is the result of surface heating by wildfires and subsequent mixing of partially degassed quartz downward into the soil. Cosmogenic noble gas depletion by wildfire heating of soils is a potential means of estimating wildfire intensity and/or frequency over pre-observational time scales.

1 Cosmogenic radionucllides and noble gases

Interactions of high-energy cosmic rays with surface rocks and minerals generate a variety of trace nuclides that are not produced by any other natural process. Because the cosmic-ray flux is rapidly attenuated with depth below the Earth's surface, these cosmic-ray-produced nuclides are a signature of surface exposure. Measurements of their concentrations are commonly used to measure the times, rates, and durations of geologic processes that act to form and degrade the Earth's surface, most commonly by "surface exposure dating" of surfaces or landforms created by processes such as glacier and ice sheet advance and retreat, river erosion, or fault movement (Dunai, 2010).

Commonly measured cosmic-ray-produced nuclides include both radionuclides (e.g., beryllium-10, aluminum-26) and stable noble gases (neon-21, helium-3). Although these are produced by similar nuclear reactions, their behavior after production is very different. ^{10}Be and ^{26}Al produced from Si and O in quartz (SiO_2) are tightly bound in the mineral lattice and can only be extracted by complete dissolution of the mineral. ^{21}Ne and ^{3}He, on the other hand, are produced by the same processes in the same mineral, but are mobile within the mineral lattice and can be lost by thermally activated diffusion (Brook and Kurz, 1993; Shuster and Farley, 2005; Tremblay et al., 2014). Because of this behaviour, noble gases (He, Ne, Ar) produced not from cosmic rays but from decay of naturally occurring U, Th, and K in many common minerals are often used to reconstruct the thermal history of rocks and minerals in the subsurface (Reiners et al., 2005). Likewise, the comparison of immobile and diffusively mobile cosmic-ray-produced nuclides can reveal aspects of the

thermal history that samples have experienced during surface and near-surface exposure. This idea has been applied for paleoclimate reconstruction (Tremblay et al., 2014, 2019; Gribenski et al., 2022), and in this paper we show another potential application in estimating wildfire frequency and/or intensity over timescales longer than the observational record. Although it is already well known that rock surface heating by natural or human-caused fire results in loss of radiogenic He and Ar (Gillespie et al., 1989; Mitchell and Reiners, 2003; Reiners et al., 2007), this has most commonly been viewed as a "bug" that is a potential source of error in noble gas geochronology and thermochronology. We show that applying the same idea to cosmogenic noble gases is potentially a "feature" that could be used for understanding long-term wildfire regimes.
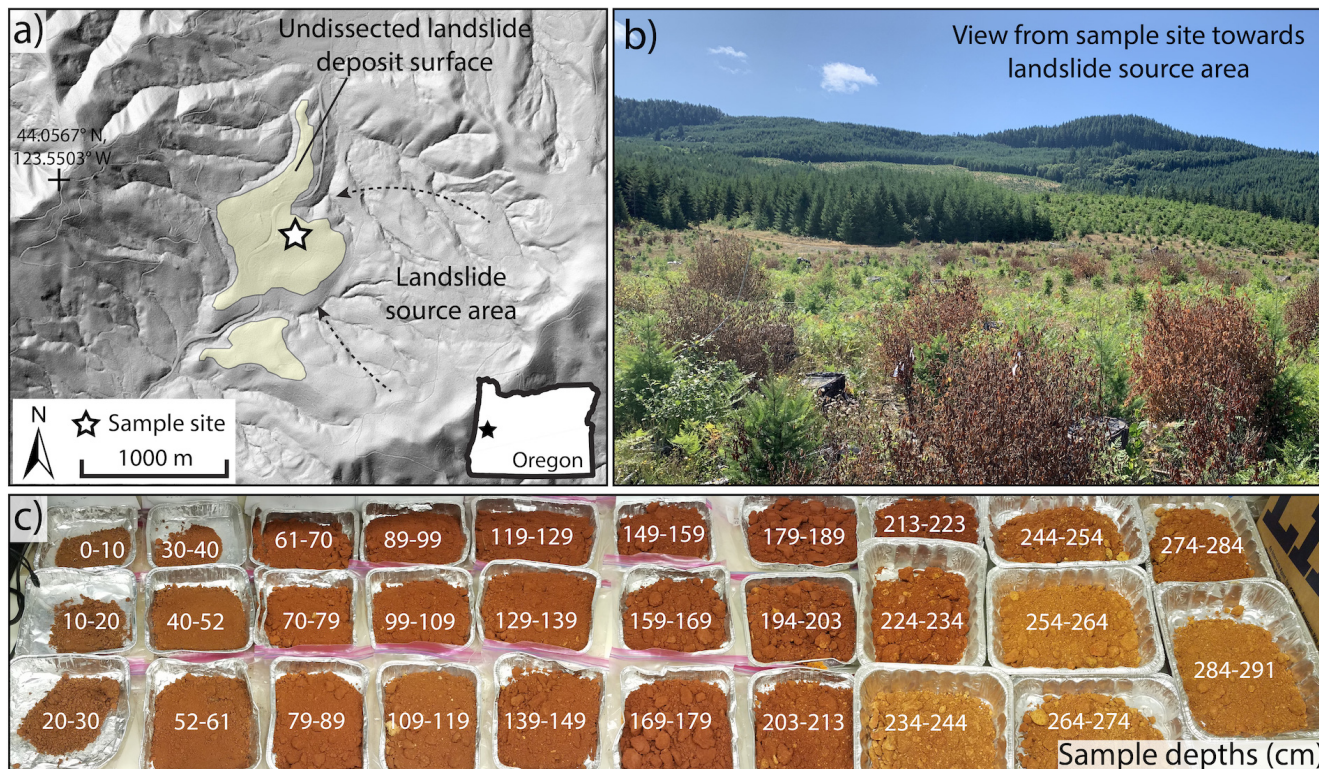
Figure 1. Cougar Pass sample site. (a) LIDAR hillshade of Cougar Pass landslide, showing the landslide deposit and source area as well as the sample location within the landslide deposit. (b) View of the landslide source area looking southeast from sample site. (c) Samples from soil profile, labeled with depth in cm. Not all of the samples shown in the photo were used for cosmogenic-nuclide measurements; see Table S1 in the supplement for details.

2 Soil profile at Cougar Pass, Oregon, USA

We collected cosmogenic ^{10}Be, ^{21}Ne, and ^{3}He data from a site at Cougar Pass (44.053° N, 123.531° W, 250 m elevation) in the Oregon Coast Range (Fig. 1). The heavily forested, soil-mantled landscape of the Oregon Coast Range is underlain by the Tyee Formation, a relatively undeformed Eocene turbidite sandstone (Heller and Dickinson, 1985). Important
5 landscape-forming processes in the region include (i) bioturbation via tree rooting and turnover of the closed-canopy coniferous forest, which roughens the land surface and contributes to the conversion of bedrock to soil (Roering et al., 2010), as well as (ii) extensive mass wasting by shallow and deep-seated landslides, which generate low-relief, bench-like terrain (Roering et al., 2005). The Cougar Pass site is located atop an ancient landslide deposit identified by Baldwin and Howell (1949) as a point of drainage capture that now separates streams draining to the Pacific Ocean and the Willamette
10 Valley. Our soil profile is in the interior of the landslide deposit, which has a broad, flat surface that displays a deep, highly weathered soil. Soil development, as well as comparisons to roughness-dated landslides in the region, indicate that the site has been stable with minimal surface erosion for > 200 ka (LaHusen et al., 2020). Paleoenvironmental archives indicate that regional forest composition has varied significantly on glacial-interglacial time scales between an subalpine, open parkland-dominated forest during glacial periods and a closed-canopy Douglas Fir forest, as is present
15 now, during interglacials (Worona and Whitlock, 1995). Wildfire has been common in the region throughout shifts in forest composition, although modulated by regional climate variations associated with sea-surface temperatures and seasonal moisture availability via winter storm tracks and summer subtropical high pressure (Long et al., 2018).

3 Cosmogenic-nuclide depth profiles at Cougar Pass

We obtained soil samples at 10-cm depth increments by auger sampling at the Cougar Pass site, and measured concen-
20 trations of cosmogenic ^{10}Be, ^{21}Ne, and ^{3}He in 0.25-0.5 mm diameter quartz grains extracted from these samples (see the Supplementary Methods). All three of these nuclides have similar production systematics, being dominantly produced by fast neutron spallation on Si and O (^{10}Be and ^{3}He) or Si only (^{21}Ne). Thus, although their absolute production rates in quartz differ (the production ratio of ^{21}Ne to ^{10}Be is 4.05, and that of ^{3}He to ^{21}Ne is approximately 7), the exponential decrease in the production rate with depth characteristic of spallogenic production is the same. However, their behavior
25 during heating is very different. ^{10}Be is not diffusively mobile and is retained during heating. ^{21}Ne is not mobile at ambient surface temperatures, but is lost from quartz grains over geologic timescales at temperatures above approximately 90° C, and over timescales of minutes to hours at 300-400° C. ^{3}He is more diffusively mobile than ^{21}Ne. Cosmogenic ^{3}He is continually lost by diffusion even at ambient Earth surface temperatures, and lost within minutes to hours at temperatures above ∼150-200° C (Shuster and Farley, 2005; Tremblay et al., 2014).
30 ^{10}Be concentrations in the soil profile (Fig. 2) show a well-mixed layer with nearly constant ^{10}Be concentration between the surface and 170 cm depth. Surface layers with well-mixed cosmogenic-nuclide concentrations are characteristic of vegetated landscapes subject to vertical soil mixing by rooting, tree throw, and similar processes (e.g., Perg et al., 2001; Rovey and Balco, 2015). This example is unusually deep and unusually homogeneous, although deep mixing is expected

from studies of root depth in the Oregon Coast Range (e.g., Roering et al., 2010). An approximate estimate of the exposure age of the surface derived from the mean ^{10}Be concentration (8.5×10^5 atoms g^{-1}) and mean production rate (2.2 atoms g^{-1} yr^{-1}) in the mixed layer is 425 ka, although this is likely not a precise age estimate because it assumes zero surface erosion (which could result in an underestimate of the age) and zero inherited ^{10}Be (which could

5   result in an overestimate). As ^{21}Ne and ^{3}He have the same production systematics as ^{10}Be, we would expect ^{21}Ne and ^{3}He concentrations to show a similar mixed-layer profile. However, we do not observe this. Instead, ^{21}Ne and ^{3}He concentrations are lowest at the surface and increase with depth through the mixed layer.
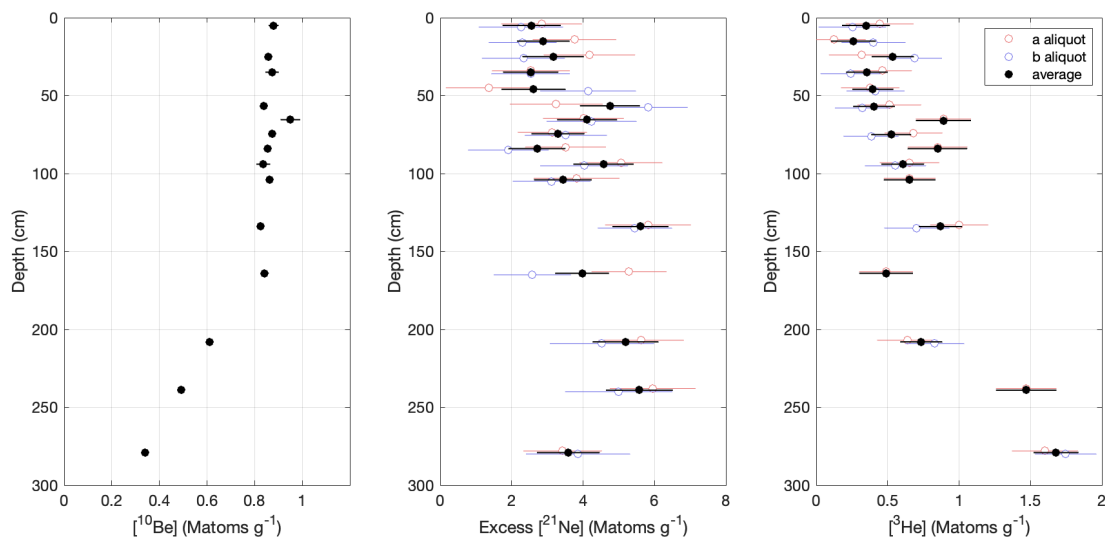
Figure 2. ^{10}Be, ^{21}Ne, and ^{3}He concentrations in the Cougar Pass soil profile. Data points marked 'average' are the error-weighted mean of measurements from multiple aliquots (see Supplementary Table S1).

4   Near-surface depletion of cosmogenic noble gases

Because we have measured ^{10}Be, ^{3}He, and ^{21}Ne in the same quartz samples and these nuclides have the same produc-

10   tion systematics, the differences in their depth profiles that we observe are impossible in a geochemically closed system. Thus, quartz in the soil profile is not a closed system. The facts that (i) both ^{21}Ne and ^{3}He are increasingly depleted relative to ^{10}Be with proximity to the surface, and (ii) ^{3}He, which is more diffusively mobile than ^{21}Ne, is more depleted than ^{21}Ne, imply that open-system behavior is due to ^{21}Ne and ^{3}He loss by surface heating. As the site has a known history of wildfire, it is nearly certain that ^{21}Ne and ^{3}He depletion is the result of wildfire heating.

15   The depth of ^{21}Ne and ^{3}He depletion far exceeds the depth of expected wildfire heating to temperatures needed to degas Ne from quartz. Wildfire heating calculations (e.g., Richter et al., 2022) typically predict temperatures up to 600°

C at the soil surface, decreasing approximately exponentially with depth with an attenuation length of 5-10 cm. Significant ^{21}Ne loss is only expected to occur within the uppermost $\sim$10 cm of the soil. Therefore, ^{21}Ne and ^{3}He depletion to more than 2 m depth requires that quartz is being degassed at the surface and then mixed down into the soil profile. This is not surprising, because well-mixed ^{10}Be concentrations show that vertical mixing is fast relative to nuclide production. However, it means that ^{21}Ne and ^{3}He concentrations in the soil retain a record of more than just the most recent heating event. This is an important contrast with observations of noble gas depletion by fire in rock surfaces (Gillespie et al., 1989; Mitchell and Reiners, 2003), because in the absence of subsurface mixing, noble gas depletion is confined to a thin surface layer and a single heating event could destroy any evidence of previous heating events. Deep vertical mixing allows the soil to retain a memory of many heating events rather than just one.
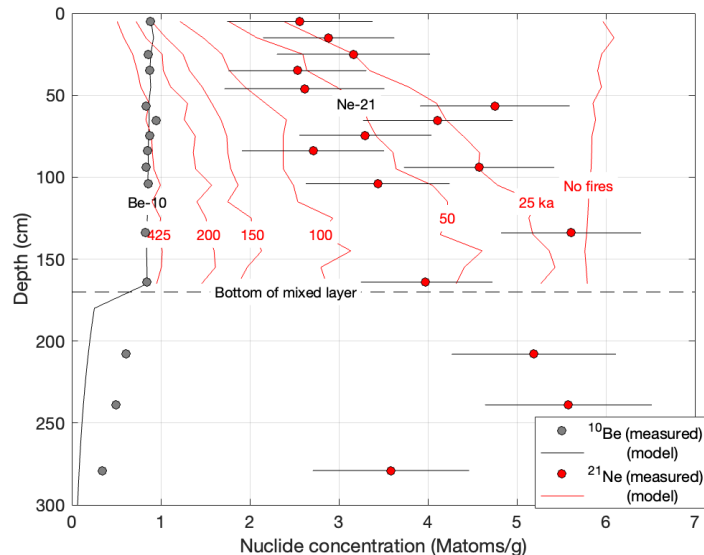
Figure 3. Simplified model simulation for ^{10}Be and ^{21}Ne accumulation and loss in a mixed soil. Exposure time and mixing rate are chosen to match measured ^{10}Be concentrations in the mixed layer (although not below the mixed layer; see text). Model ^{21}Ne concentrations in the mixed layer are calculated for the same exposure time and mixing rate, but different onset times (given for each line in ka) for the simulated fire regime. For example, the line marked '50 ka' is the result of a simulation in which the fire regime starts 50,000 years before present.

Finally, the observation that noble-gas-depleted quartz is not fully mixed to the bottom of the mixed layer identified from ^{10}Be concentrations requires that the system is not in steady state. If both mixing and heating had been steady and continuous since the formation of the soil, all nuclides would be similarly homogenized within the mixed layer. They are not, so heating intensity must have increased at some time after soil formation. We highlight this effect with a simplified one-dimensional model of ^{10}Be and ^{21}Ne accumulation and loss in a mixed soil (we omit ^{3}He because ^{3}He is continuously

diffusively lost at ambient temperature even without fire heating, so a more complex model with additional paleoclimate assumptions is required).

The model simulation, which is described in the Supplementary Methods and the results of which are shown in Figure 3, considers a large number of soil particles that describe random walks vertically through a 170-cm mixed layer, and computes ^{10}Be production as a function of depth for each step in the random walk. A model duration of 425 ka (see above) and random walk distance of 0 +/- 10 cm in each 250-year time step replicates ^{10}Be concentrations in the mixed layer. The model underestimates ^{10}Be concentrations below the mixed layer, which indicates that the assumption that vertical mixing stops abruptly at 170 cm is oversimplified, but this does not affect the behavior within the mixed layer that the model is intended to simulate. We similarly compute ^{21}Ne production in the same particles, but also assume that during each time step there is one wildfire with a 1-hour duration, a surface temperature of 450°C, and an exponential attenuation depth of 6 cm (this is a characteristic scenario from Richter et al., 2022). Each quartz grain loses ^{21}Ne as a single spherical diffusion domain (Fechtig and Kalbitzer, 1966) with temperature-dependent diffusivity as measured by Shuster and Farley (2005). It is also necessary to assume a background concentration of ^{21}Ne, which has not been measured for the soil protolith, so is chosen to yield an approximate fit to the data. This scenario is roughly based on late Pleistocene fire frequency as reconstructed by Long et al. (2018), but it is not unique: the same diffusive loss can be achieved by many combinations of fire frequency, fire duration, and/or temperature profile.

To highlight the effect of transient changes in fire regime, we simulate a change in fire intensity by imposing the fire regime partway through the simulation. As shown in Figure 3, if there are no fires ever, ^{21}Ne concentrations are high and well-mixed. If wildfire heating occurs throughout the entire exposure history of the soil, concentrations are low and well-mixed. The observed gradient in ^{21}Ne concentration requires a transient scenario in which the fire regime has recently intensified for a time that is not long enough to permit complete mixing of quartz degassed at the surface down into the soil. This is broadly consistent with the hypothesis developed from paleoenvironmental data that during glacial periods, a parkland-meadow dominated forest generated low-intensity fires, but during interglacial periods a closed-canopy Douglas fir forest generates similarly frequent but higher-intensity fires (Long et al., 2018). Thus, although diffusive processes are inherently information-destroying and therefore transient scenarios that explain the data are unlikely to be unique, a simple model-data comparison shows that cosmogenic noble gas depletion within a deep soil profile can contain information about past changes in fire regime.

5 Useful applications

Observations of cosmogenic noble gas depletion in soils may have several useful applications in studying wildfire. First, prehistoric wildfire frequency/intensity reconstructions are typically based on charcoal counts in sedimentary deposits (Marlon et al., 2012). This provides an effective reconstruction of fire frequency, but reconstructing fire intensity is indirect and more difficult. Cosmogenic noble gas depletion is complementary to this approach in that, in general, it is unlikely to record individual events, but records a combination of aggregate frequency and intensity. If frequency is known from other

data, in principle intensity could be inferred. It is also complementary to lake-sediment-based records in that it provides site-specific rather than areally-averaged information.

Second, an empirical measure of the long-term average temperature/depth history that has actually been experienced in past wildfires may be useful for buried infrastructure design and protection. Although vertical mixing may complicate this in forested landscapes, many environments (e.g., grasslands) do not experience deep vertical mixing.

Third, cosmogenic noble gas depletion is a potential means of evaluating whether recent wildfires are more intense than fires that took place in a pre-management regime. The depth profile of cosmogenic noble gases should reflect a mean fire intensity integrated over many past fires. If a fire is significantly more intense than past fires, ^{3}He and ^{21}Ne may be systematically more depleted in the shallow subsurface in areas affected by the recent fire than in adjacent areas that were not affected but share the same long-term fire regime.

This approach also has some application challenges. First, there are several technical challenges, including the difficulty of measuring cosmogenic ^{21}Ne at low concentrations in the presence of commonly large inherited or background inventories, as well as the fact that He and Ne diffusion kinetics are variable in quartz from different sources (Tremblay et al., 2014) and may require lithology-specific characterization. Second, as noted above, the fact that diffusion and mixing are inherently information-destroying processes means that it is unlikely that a unique history of millennial-scale changes in fire regime could be reconstructed from a ^{21}Ne or ^{3}He depth profile. On the other hand, this does not affect its potential utility in hypothesis-testing: in many cases these data could be clearly consistent or inconsistent with hypotheses about changes in fire regime developed from other paleoenvironmental information.

Code and data availability. All measurements described in the paper, as well as MATLAB code implementing the simplified model simulation, are included in the supplementary data.

Author contributions. Struble and Roering were primarily responsible for fieldwork and sample collection and preparation. Hidy and Balco were primarily responsible for cosmogenic-nuclide measurements. Balco prepared the manuscript with contributions from all authors.

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