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^{26}Al–^{10}Be–^{21}Ne burial dating

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ABSTRACT

Cosmogenic-nuclide burial dating relies on a pair of cosmic-ray-produced nuclides that are produced in the same rock or mineral target at a fixed ratio, but have different half-lives. For example, ^{26}Al and ^{10}Be are produced in quartz at ^{26}Al:^{10}Be = 6.75:1. If a sample of quartz is exposed at the surface for a time, ^{26}Al and ^{10}Be concentrations reflect this ratio; if it is then buried below the penetration depth of cosmic rays, production stops and both nuclides decay. The half-life of ^{26}Al is half that of ^{10}Be, so the ^{26}Al/^{10}Be ratio decreases over time and can be used to date the burial event. Because quartz derived from surface erosion and then buried by sediment accumulation is common, the method is widely applicable for dating Plio-Pleistocene clastic sediments. All (terrestrial) applications of burial dating so far have used the ^{26}Al–^{10}Be pair. Here we show that coupling cosmogenic ^{21}Ne, which is also produced in quartz, with ^{26}Al or ^{10}Be should improve upon both the age range and accuracy of ^{26}Al–^{10}Be burial dating. We establish the feasibility of this approach by ^{21}Ne measurements at two sites that have already been dated using ^{26}Al–^{10}Be burial dating. Burial ages from all three nuclide pairs agree at both sites, which shows that currently accepted values for decay constants and production ratios are internally consistent. Thus, it is possible at present to increase the useful range of cosmogenic-nuclide burial dating by incorporating ^{21}Ne. Fully realizing the potential improvements in accuracy would benefit from additional estimates of ^{21}Ne/^{26}Al and ^{21}Ne/^{10}Be production ratios that are independent of the ^{26}Al and ^{10}Be decay constants.

1. Cosmogenic-nuclide burial dating

1.1. Background: ^{26}Al–^{10}Be burial dating

Cosmogenic-nuclide burial dating is a means of dating geological deposits by measuring pairs of rare nuclides that are produced at a fixed ratio during cosmic-ray bombardment of a rock or mineral target, but have different half-lives (see Granger, 2006 for a complete overview). The nuclides most commonly used for this purpose, ^{26}Al and ^{10}Be, are produced in quartz at a ratio ^{26}Al:^{10}Be = 6.75:1. A sample of quartz that experiences a single period of exposure at the Earth's surface has ^{26}Al and ^{10}Be concentrations governed by this ratio. If this sample is then buried deeply enough to be shielded from the cosmic-ray flux, nuclide production stops and inventories of both nuclides decrease by radioactive decay. The half-life of ^{26}Al (0.705 Ma) is shorter than that of ^{10}Be (1.39 Ma), so the ^{26}Al/^{10}Be ratio decreases exponentially with the duration of burial.

Burial dating only requires quartz that has been exposed at the surface for a time and then buried. Neither the formation of new minerals nor the preservation of age-diagnostic fossils is required. Quartz is ubiquitous, and the formation of nearly all sedimentary deposits naturally involves surface exposure of the sediment followed by burial after deposition; thus, the method is potentially attractive for dating Plio-Pleistocene clastic sediments that cannot be dated by other means. Applications of burial dating have, in fact, focused on problems in geology and anthropology that could not be solved by existing dating methods, including i) determining valley incision rates from the age of stranded cave and terrace sediments (Granger et al., 2001; Stock et al., 2005a; Haeuselmann et al., 2007); ii) dating early and middle Pleistocene ice sheet expansions (Balco et al., 2005a; Balco and Rovey, 2008); and iii) dating hominin fossils and stone tool assemblages in regions that lack a volcanic ash chronology (Gibbon et al., 2009; Shen et al., 2009).

Although there are a number of cosmogenic-nuclide pairs that could be used for burial dating, all terrestrial applications of the technique so far have used ^{26}Al and ^{10}Be in quartz. For the most part this is because these nuclides are relatively easy to measure and the ^{26}Al/^{10}Be production ratio in quartz is well established. However, using other nuclide pairs would in principle significantly improve both the useful age range and the accuracy of the method. One possibility is to use the stable cosmogenic nuclide ^{21}Ne, which is also produced in quartz, with ^{26}Al or ^{10}Be. Several studies have combined ^{26}Al, ^{10}Be, and ^{21}Ne measurements on surface quartz samples, and some of them have used ^{21}Ne/^{26}Al or ^{21}Ne/^{10}Be ratios to show that these surface samples must have been buried at one time (e.g. Fujioka et al., 2005; Kober et al., 2008), but there have been no attempts to use ^{21}Ne for burial dating. In this paper we show that ^{26}Al–^{21}Ne and ^{10}Be–^{21}Ne burial dating can yield improvements in both age range and accuracy over ^{26}Al–^{10}Be burial dating, and we establish its feasibility.

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1.2. Advantages of cosmogenic ^{21}Ne

^{26}Al–^{21}Ne and ^{10}Be–^{21}Ne burial dating offer two potential improvements on ^{26}Al–^{10}Be burial dating: an increased useful age range and improved accuracy. The useful age range of a burial-dating nuclide pair is set by the decay constants of the two nuclides: measurement precision for each nuclide decreases with its concentration, and eventually the shorter-lived of the pair decays to a level too low to measure accurately. The useful range of ^{26}Al–^{10}Be burial dating is ca. 0.5–6 Ma under ideal conditions (Fig. 1). The ^{26}Al–^{21}Ne pair has a somewhat increased useful range due to the fact that only the ^{26}Al inventory is reduced by decay. However, because i) the half-life of ^{10}Be is approximately twice that of ^{26}Al, and ii) ^{10}Be can be measured more precisely at low concentrations than ^{26}Al (e.g. Schaefer et al., 2009), the useful range of the ^{10}Be–^{21}Ne pair is potentially more than double that of the ^{26}Al–^{10}Be pair. ^{10}Be–^{21}Ne burial dating should be effective well into the Miocene.

The total uncertainty in a burial age (that is, the uncertainty that should be used in comparing it to dates obtained with an independent method) mainly comprises i) measurement uncertainties, and ii) uncertainties in the decay constants for the nuclides in question. Other uncertainties, in nuclide production rates and the burial history of the sample, make a minor contribution to the total uncertainty in most cases (Balco et al., 2005b; Balco and Rovey, 2008).

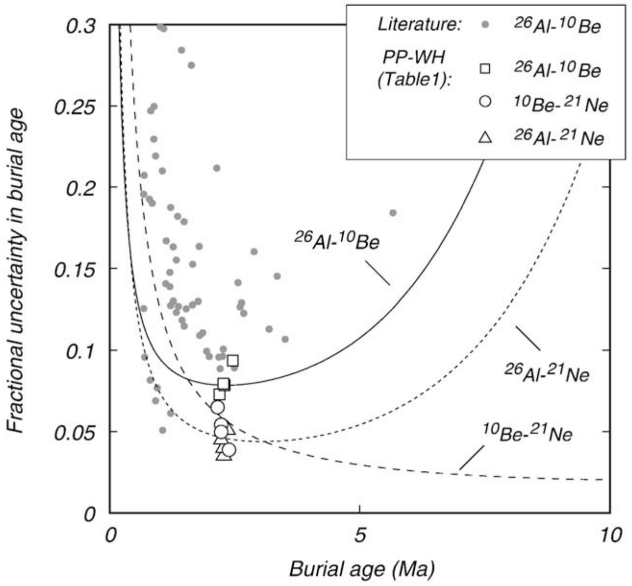

Fig. 1. Uncertainty analysis for burial dating using various pairs of cosmogenic nuclides in quartz. Uncertainties depicted here are the 'total uncertainty' or the 'external uncertainty' of various authors and reflect measurement and decay constant uncertainties. These uncertainties apply when comparing a cosmogenic-nuclide burial age to an age determined using an independent method. The closed circles are representative published ^{26}Al–^{10}Be burial ages taken from Granger et al. (2001), Anthony and Granger (2004), Stock et al. (2005b), Balco and Rovey (2008), and Rovey et al. (in press). We have recalculated these ages and their uncertainties using the ^{10}Be decay constant of Chmeleff et al. (2009) and Korschinek et al. (2009). The open symbols are burial ages for the Pendleton Pit samples from Table 1. The lines show the model relationship between burial age and uncertainty for samples with similar histories as the Pendleton Pit samples, *i.e.*, a two-stage exposure history consisting of steady erosion at 2 m Ma^{-1} at 300 m elevation followed by deep burial. In computing these relationships, we approximated ^{26}Al and ^{10}Be measurement uncertainties by a $1/\sqrt{n}$ relationship fit to several hundred ^{26}Al and ^{10}Be measurements made at UW and LLNL-CAMS, and assumed a 6% measurement uncertainty for ^{21}Ne. Scatter of published ^{26}Al–^{10}Be burial ages around the model relationship primarily reflects variation in the cosmic-ray dose prior to burial and thus in the nuclide concentrations. The model assumption of deep burial implies negligible post-burial production due to muons. For shallow burials, uncertainties in production rates due to muons would steepen the increase in uncertainty at the end of the useful age range of each pair as the nuclide inventory due to muons becomes a large fraction of the total nuclide inventory.

Because of the need to deconvolve cosmogenic ^{21}Ne from other sources of ^{21}Ne by measurements of multiple Ne isotopes (Niedermann et al., 1993), measurement uncertainties are commonly larger for ^{21}Ne than for ^{26}Al and ^{10}Be. However, as ^{21}Ne is stable, the ^{21}Ne inventory does not decrease after burial, so there is no loss of measurement precision with increasing burial age. In addition, the fact that ^{21}Ne is stable eliminates one of the decay constant uncertainties. Decay constants for ^{26}Al and ^{10}Be are known with ~3% and ~1% precision, respectively, (Nishiizumi, 2004; Chmeleff et al., 2009; Korschinek et al., 2009), and propagation of these uncertainties into an ^{26}Al–^{10}Be burial age implies an age uncertainty of 5% that cannot be reduced by improving the precision of the ^{26}Al and ^{10}Be measurements. The ^{26}Al–^{21}Ne and ^{10}Be–^{21}Ne pairs are only subject to part of this decay constant uncertainty. Finally, the total uncertainty in a burial age is inversely proportional to the difference between the decay constants of the two nuclides. This difference is similar for the ^{26}Al–^{10}Be and ^{10}Be–^{21}Ne pairs. However, it is twice as large for the ^{26}Al–^{21}Ne pair, which decreases the total uncertainty in an ^{26}Al–^{21}Ne burial age. To summarize, although measurements of ^{21}Ne at typical surface concentrations are often less precise than ^{26}Al and ^{10}Be measurements, the total uncertainty in ^{26}Al–^{21}Ne and ^{10}Be–^{21}Ne burial ages should be less than that in ^{26}Al–^{10}Be burial ages. Fig. 1 shows this relationship.

2. This study: examples of ^{21}Ne–^{10}Be–^{26}Al burial dating

To investigate the feasibility of burial dating with ^{21}Ne as well as the internal consistency of currently accepted production rates and decay constants for ^{26}Al, ^{10}Be, and ^{21}Ne, we measured ^{21}Ne concentrations in quartz samples from two sites where we had already measured ^{26}Al–^{10}Be burial ages. We selected these sites for two reasons. First, the samples were derived from slowly eroding cratonic landscapes, so had relatively high nuclide concentrations at the time of burial. This facilitates precise measurement of nuclide concentrations, making it possible to accurately assess consistency between ages derived from the various nuclide pairs. Second, the geologic context at these sites shows that the samples were buried rapidly and deeply enough that post-burial nuclide production by deeply penetrating muons contributes only a small fraction of the total nuclide inventory. This ensures that the burial ages are only weakly sensitive to uncertainties in production rates due to muons.

Riverbluff Cave in Springfield, Missouri, USA, contains a sequence of fossiliferous gravels and backwater sediments that were derived from a slowly eroding bedrock upland, and deposited in the cave by a nearby river that formerly flowed through it. The cave is now stranded above river level due to river diversion and subsequent valley incision. A series of five quartz sand samples from the cave sediments yielded stratigraphically ordered ^{26}Al–^{10}Be burial ages between 0.65 and 1.1 Ma (Rovey et al., in press). We measured ^{21}Ne in one sample from this site.

At the Pendleton clay pit near Pendleton, Missouri, USA, the Whippoorwill formation, a colluvial deposit derived from weathering of underlying bedrock, was buried by till during an early Pleistocene advance of the Laurentide Ice Sheet. Four ^{26}Al–^{10}Be burial ages from the Whippoorwill at this site (Rovey and Balco, in press), as well as two others from a stratigraphically equivalent site nearby (Balco et al., 2005a), date till emplacement at 2.42 ± 0.14 Ma (average of results from both sites). We measured ^{21}Ne in all four samples from the Pendleton site.

3. Methods

3.1. Analytical methods

We isolated quartz from sand-sized sediment, extracted Be and Al using standard methods of HF dissolution and column chromatography at the Cosmogenic Nuclide Lab at the University of Washington

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(Stone, 2004), and measured Be and Al isotope ratios by accelerator mass spectrometry at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory. ^{26}Al and ^{10}Be concentrations appear in Table 1. We extracted ^{21}Ne from aliquots of the same purified quartz samples in the Noble Gas Thermochronometry Lab of the Berkeley Geochronology Center either by heating the sample in a resistance furnace, or by encapsulating it in a Ta packet and heating it with a 75 W diode laser. We analysed the released Ne on a MAP-215 mass spectrometer using an ^{39}Ar spike to correct for isobaric interferences on masses 20 and 22. Balco and Shuster (2009) give complete details of the measurement technique. Summary ^{21}Ne concentrations appear in Table 1 and complete results of the step-degassing analyses in Table S1.

The Riverbluff Cave sample is composed of marine chert derived from local limestone, and contained an unusually large quantity of trapped Ne (Table S1). The isotope composition of Ne in this sample lay significantly above the atmospheric–cosmogenic mixing line (Table S1; Fig. S1), which is consistent with the idea that trapped Ne was fractionated from air either during atmosphere–ocean gas exchange or diagenesis (e.g. Matsubara et al., 1991). Thus, we calculated cosmogenic ^{21}Ne as excess ^{21}Ne with respect to a mass fractionation line passing through atmospheric Ne (Niedermann et al., 1994). Even though this sample contains an easily measurable amount of cosmogenic ^{21}Ne, and the large signal contributed by trapped Ne permits precise Ne isotope ratio measurements, the fact that ~95% of the ^{21}Ne in this sample is *not* cosmogenic in origin compounds uncertainties such that the precision of the cosmogenic ^{21}Ne measurement (12%) is not adequate to improve on the ^{26}Al–^{10}Be burial age. For this reason, we did not pursue the Riverbluff Cave samples any further.

Samples from the Pendleton site contained significantly less trapped Ne and had Ne isotope compositions indistinguishable from the atmospheric–cosmogenic mixing line (Table S1; Fig. S1). Thus, we calculated cosmogenic ^{21}Ne in these samples on the basis of two-component mixing between atmospheric and cosmogenic Ne. Duplicate analyses of two samples agreed within their respective uncertainties, and total measurement uncertainties were 4–7%.

3.2. Calculation of burial ages

Burial ages for the Riverbluff Cave sample assume steady erosion followed by a single period of burial at their present depth; those for Pendleton pit samples use the multi-stage burial scheme described in Balco et al. (2005a), with overburden ages and thicknesses tabulated in Rovey and Balco (in press). Production rates for ^{26}Al and ^{10}Be reflect the scaling scheme of Stone (2000) and the calibration data set of Balco et al. (2008) renormalized to the Be isotope ratio standards of Nishiizumi et al. (2007). This implies an ^{26}Al/^{10}Be production ratio of 6.75. ^{26}Al and ^{10}Be production rates by muons follow Heisinger et al. (2002a,b), as implemented in Balco et al. (2008). The ^{21}Ne/^{26}Al and ^{21}Ne/^{10}Be production ratios are not as well established as the ^{26}Al/^{10}Be production ratio; we used ^{21}Ne/^{26}Al = 0.606 and ^{21}Ne/^{10}Be = 4.08 (Balco and Shuster, 2009). The production rate of ^{21}Ne by muons is not well known. Balco and Shuster (2009) found that the proportion of production due to muons was similar for ^{21}Ne and ^{10}Be, so we calculated ^{21}Ne production rates due to muons by assuming that the ^{21}Ne/^{10}Be production ratio was constant with depth. Because of the site selection criteria discussed above, this is a minor issue for our purposes. For the ^{26}Al and ^{10}Be decay constants we used values of $9.83 \pm 0.25 \times 10^{-7}$ (Nishiizumi, 2004) and $4.987 \pm 0.043 \times 10^{-7}$ (Chmeleff et al., 2009; Korschinek et al., 2009) yr^{-1}, respectively.

Table 1 shows the burial ages. The stated total uncertainties in burial age include measurement uncertainties in the nuclide concentrations and uncertainties in the decay constants. Because we are mainly interested in determining whether or not burial ages calculated using different nuclide pairs for the same sample are mutually consistent, we did not include either i) site-specific uncertainties associated with the burial history of the samples, or ii) uncertainties in the production ratios. We computed the uncertainties using linear error propagation with the partial derivatives estimated by a first-order centered difference approximation.

4. Results and discussion

^{26}Al–^{21}Ne, ^{10}Be–^{21}Ne, and ^{26}Al–^{10}Be burial ages for each sample agreed within their respective uncertainties (Table 1; Figs. 2 and 3). Weighted averages for each nuclide pair of four samples from the Pendleton site agreed at 1.5%, as well or better than can be expected given the measurement uncertainties. This is important because it shows that the independently determined parameters used to compute the burial ages—the nuclide production ratios and the ^{26}Al and e decay constants—are internally consistent. Thus, these parameters are adequately well determined to realize the increase in the useful range of cosmogenic-nuclide burial dating offered by combining ^{21}Ne with ^{26}Al or ^{10}Be measurements.

Agreement between burial ages determined from the three nuclide pairs does not, by itself, prove conclusively that all these parameters have been accurately determined and thus that the burial ages are accurate. However, i) these parameters were for the most part determined independently by a variety of techniques, and ii) for these parameters to be inaccurate and still yield consistent burial ages for all three nuclide pairs would require a systematic offsetting relationship among errors in estimating the various parameters. These observations strongly suggest that the production ratios and decay constants have been accurately determined.

Table 1
^{26}Al, ^{10}Be, and ^{21}Ne concentrations and burial ages calculated therefrom.

Sample name	[^{10}Be][a] (10^6 atoms g^{-1})	[^{26}Al][b] (10^6 atoms g^{-1})	[^{21}Ne] (10^6 atoms g^{-1})	No. of ^{21}Ne measurements	Burial age (Ma)		
					^{26}Al–^{10}Be	^{10}Be–^{21}Ne	^{26}Al–^{21}Ne
Whippoorwill formation, Pendleton clay pit, Missouri							
PP-WH-0	0.705 ± 0.013	1.634 ± 0.061	11.31 ± 0.50	2	2.21 ± 0.10 (0.16)	2.41 ± 0.09 (0.09)	2.29 ± 0.06 (0.08)
PP-WH-0.5	0.699 ± 0.018	1.459 ± 0.104	10.25 ± 0.63	1	2.47 ± 0.18 (0.23)	2.26 ± 0.12 (0.12)	2.37 ± 0.11 (0.12)
PP-WH-1	0.709 ± 0.018	1.568 ± 0.075	10.46 ± 0.56	2	2.31 ± 0.12 (0.18)	2.26 ± 0.11 (0.11)	2.28 ± 0.08 (0.09)
PP-WH-1.75	0.700 ± 0.018	1.566 ± 0.077	9.90 ± 0.69	1	2.28 ± 0.13 (0.18)	2.19 ± 0.13 (0.14)	2.24 ± 0.09 (0.10)
	Error-weighted mean of four samples (internal uncertainties)				2.28 ± 0.06	2.31 ± 0.05	2.29 ± 0.04
Riverbluff Cave, Springfield, Missouri							
RC-L5f	1.909 ± 0.036	7.69 ± 0.31	12.5 ± 1.4	1	0.64 ± 0.08 (0.09)	0.46 ± 0.18 (0.18)	0.56 ± 0.13 (0.14)

Full ^{26}Al and ^{10}Be process blanks were less than 0.2% of the total number of atoms measured in any sample. Complete results of the step-degassing Ne analyses appear in Table S1. Both internal (including measurement uncertainties only) and external (in parentheses; including measurement and decay constant uncertainties) uncertainties are shown for burial ages of individual samples. Site and sample information and ^{26}Al and ^{10}Be concentrations are also published in Rovey et al. (in press) and Rovey and Balco (in press).

[a] Normalized to the isotope ratio standards of Nishiizumi et al. (2007).

[b] Normalized to the isotope ratio standards of Nishiizumi (2004).

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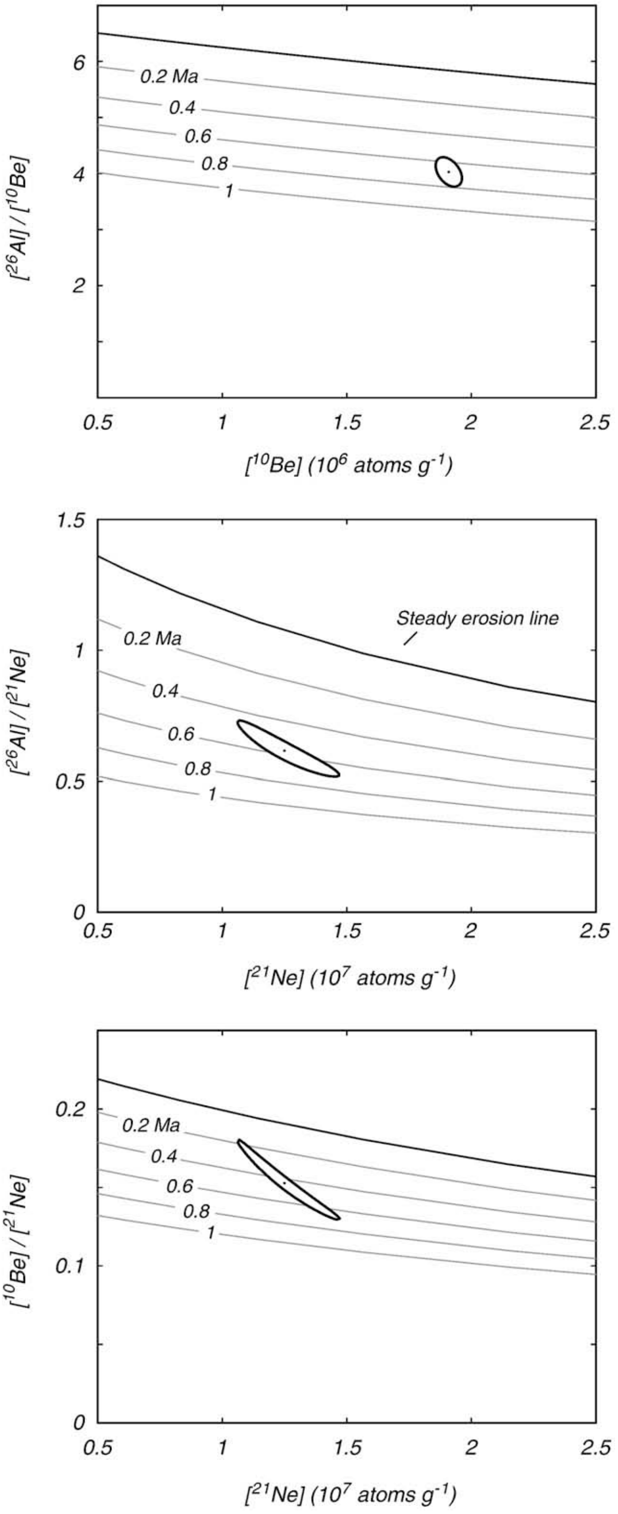

Fig. 2. ^{26}Al, ^{10}Be, and ^{21}Ne concentrations in one sample from Riverbluff Cave plotted on ^{10}Be–^{26}Al/^{10}Be, ^{21}Ne–^{26}Al/^{21}Ne, and ^{21}Ne–^{10}Be/^{21}Ne diagrams. The dark line in each panel is the steady erosion line. The lighter lines are isolines of burial age, calculated for the present burial depth of the sample (7100 g cm^{-2}). The ellipses are 68% confidence intervals reflecting measurement uncertainty.

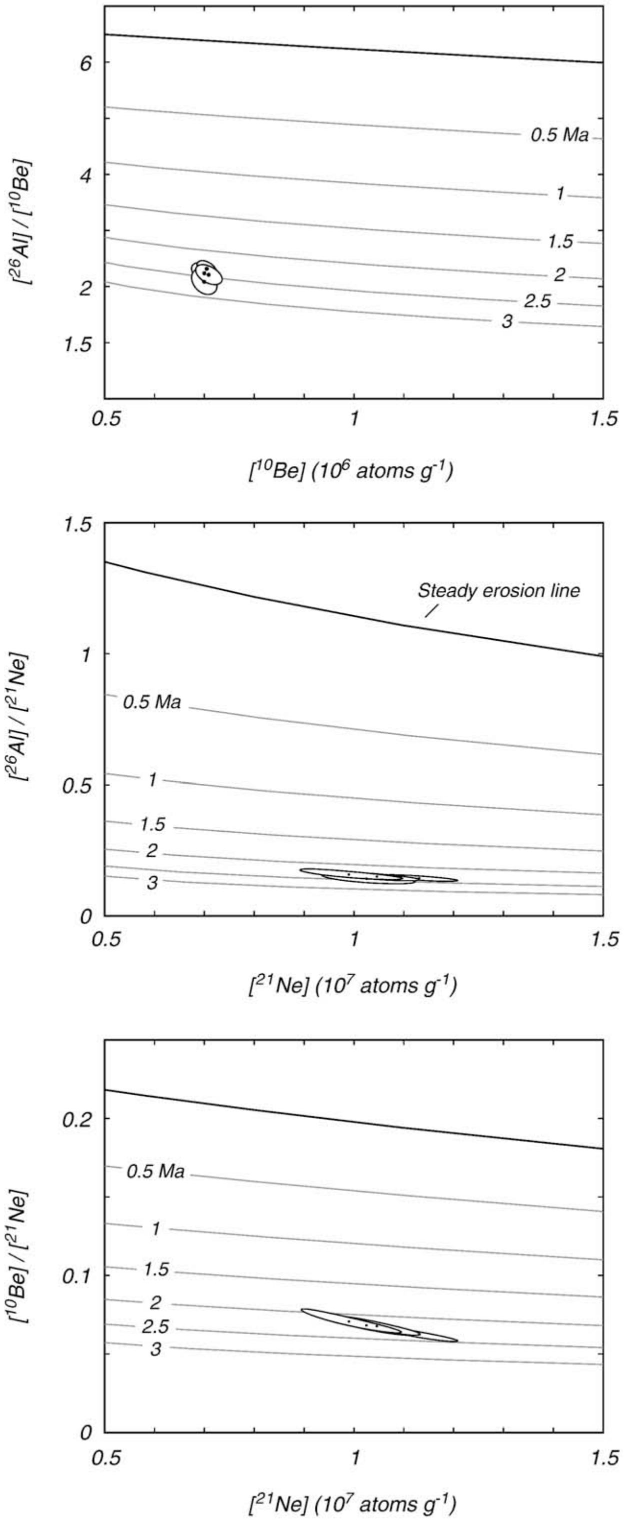

Fig. 3. ^{26}Al, ^{10}Be, and ^{21}Ne concentrations in four samples from the Whippoorwill formation at the Pendleton clay pit, plotted on ^{10}Be–^{26}Al/^{10}Be, ^{21}Ne–^{26}Al/^{21}Ne, and ^{21}Ne–^{10}Be/^{21}Ne diagrams. The dark line in each panel is the steady erosion line. The lighter lines are isolines of burial age, calculated for the present burial depth of the samples (2200 g cm^{-2}). The ellipses are 68% confidence intervals reflecting measurement uncertainty.

To further explore this issue, we examined the sensitivity of the burial ages for the Pendleton site derived from the various nuclide pairs to adjusting the values of half-lives and production ratios (Fig. 4). First, as expected given the selection criteria for this site—that nuclide production by muons be relatively unimportant—neither the ages themselves nor their agreement is significantly affected by adjusting the ^{21}Ne production rate due to muons (Fig. 4a). Thus, these results do not provide any new constraints on ^{21}Ne production by muons. Of the remaining parameters involved in the calculation, now that the ^{10}Be decay constant has recently been precisely determined (Chmeleff et al., 2009; Korschinek et al., 2009), the least certain is the

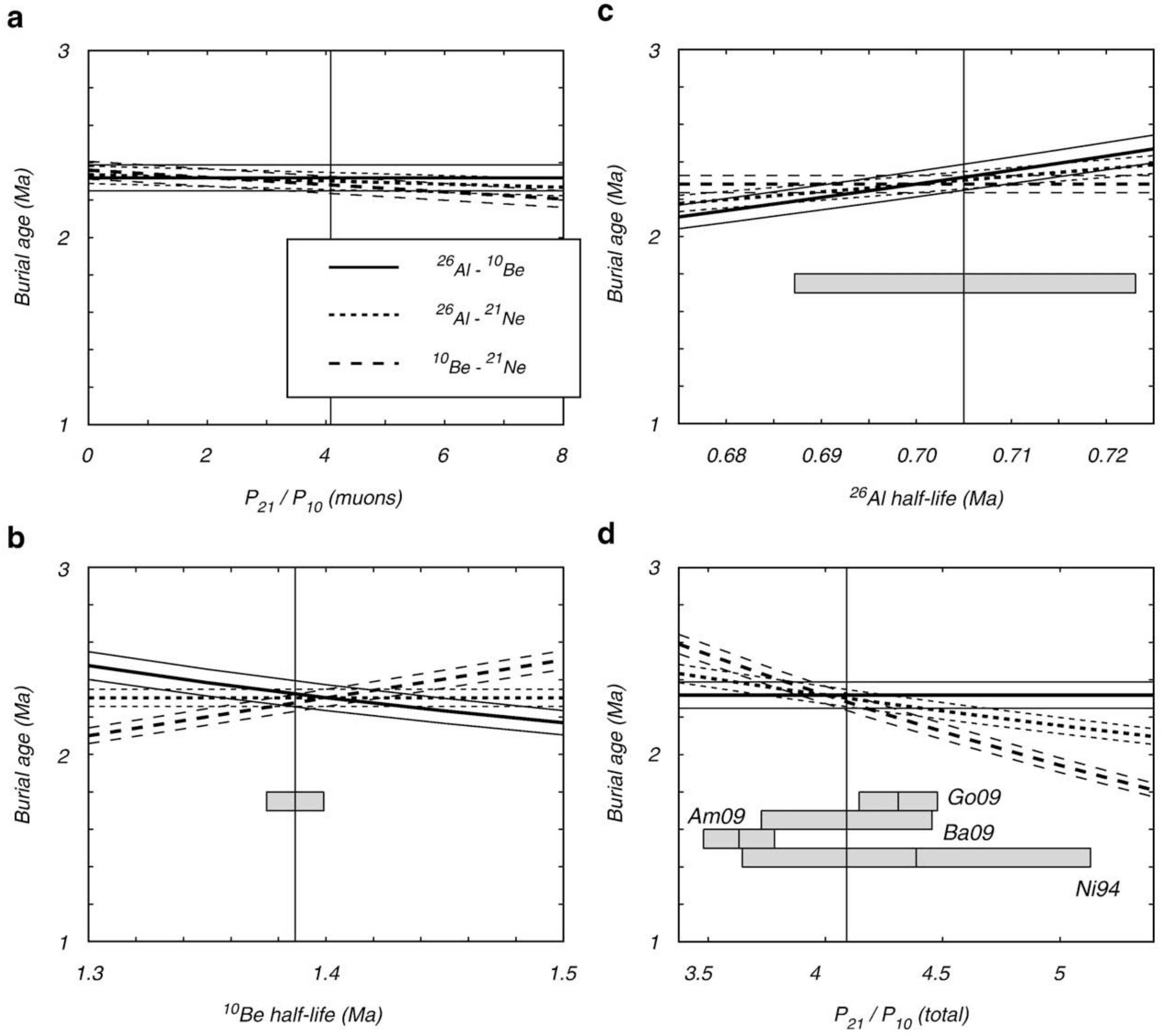

Fig. 4. Sensitivity of weighted mean burial ages for four samples from the Whippoorwill formation at the Pendleton site to nuclide production ratios and the values of the ^{26}Al and ^{10}Be half-lives. Heavy lines indicate weighted mean burial ages and light lines show one standard error of the weighted mean (see Table 1). The vertical line in each figure shows the value of that parameter used in calculating the burial ages in Table 1. Panel (a), sensitivity of burial ages to the production rate of ^{21}Ne by muons, expressed as the ratio of the production rate of ^{21}Ne by muons to that of ^{10}Be. Because of the site selection criteria, this parameter has little effect on the burial ages. Panels (b) and (c), sensitivity of burial ages to the ^{26}Al and ^{10}Be half-lives. Gray bars show 1σ uncertainties from Nishiizumi (2004) (^{26}Al) and Chmeleff et al. (2009) and Korschinek et al. (2009) (^{10}Be). Panel (d), sensitivity of burial ages to the ^{21}Ne/^{10}Be production ratio. The gray bars show values and 1σ uncertainties on the ^{21}Ne/^{10}Be production ratio measured by Niedermann et al. (1994), Balco and Shuster (2009), Goethals et al. (2009), and Amidon et al. (2009). Niedermann et al. (1994) actually measured the ^{21}Ne/^{26}Al production ratio; here we show the corresponding ^{21}Ne^{10}Be ratio given an ^{26}Al/^{10}Be production ratio of 6.75.

^{21}Ne production rate and the ^{21}Ne/^{26}Al and ^{21}Ne/^{10}Be production ratios that it implies. Recent estimates of the ^{21}Ne/^{10}Be production ratio by Balco and Shuster (2009) (^{21}Ne/^{10}Be = 4.08 ± 0.37; we used this value to compute the burial ages in Table 1) and Goethals et al. (2009) (^{21}Ne/^{10}Be = 4.31 ± 0.17) agree within their measurement uncertainties, and either value would result in acceptable consistency between burial ages computed from all three nuclide pairs (Fig. 4d). On the other hand, calculating burial ages using an estimate of the ^{21}Ne/^{10}Be ratio by Amidon et al. (2009) (^{21}Ne/^{10}Be = 3.63 ± 0.10) would result in small systematic differences among burial ages (Fig. 4d). However, as one could offset this discrepancy by adjusting the ^{26}Al half-life by an amount smaller than its present measurement uncertainty, it is difficult to choose between the various published values for the ^{21}Ne production rate based on the measurements in the present study alone. To summarize, although accepted values for the ^{26}Al and ^{10}Be half-lives and the ^{21}Ne/^{10}Be production ratio of Balco and Shuster (2009) yield consistent burial ages for all three nuclide pairs at the Pendleton site, the offsetting relationships among several uncertain parameters make it impossible to conclusively determine the ^{21}Ne/^{10}Be production ratio from the relationship between burial ages obtained from the three nuclide pairs. Overall this highlights the importance of independent determinations of the production ratios and decay constants in fully realizing the potential improved accuracy of burial dating with ^{21}Ne.

5. Conclusions

When cosmogenic-nuclide concentrations are high enough to permit precise measurement of ^{21}Ne in quartz, burial dating with either the ^{26}Al–^{21}Ne or ^{10}Be–^{21}Ne nuclide pairs in quartz should have a longer useful age range, and be more accurate, than burial dating with the ^{26}Al–^{10}Be pair. Combined ^{26}Al–^{10}Be–^{21}Ne measurements from two sites show that accepted values for ^{26}Al and ^{10}Be decay constants and a set of production ratios of ^{26}Al/^{10}Be = 6.75, ^{21}Ne/^{26}Al = 0.606, and ^{21}Ne/^{10}Be = 4.08 yield internally consistent burial ages from all three nuclide pairs. Thus, it is now possible to increase

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the useful range of cosmogenic-nuclide burial dating by incorporating ^{21}Ne. However, fully realizing the potential improvements in accuracy would benefit from additional estimates of the ^{26}Al decay constant as well as estimates of the ^{21}Ne/^{26}Al or ^{21}Ne/^{10}Be production ratios that are independent of the ^{26}Al and ^{10}Be decay constants.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2009.07.025.

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