Cosmogenic $^{21}$Ne production systematics inferred from a 25-meter sandstone core

Greg Balco, David Shuster

Berkeley Geochronology Center, Berkeley CA USA -- balcs@bgc.org
CRPG-CNRS-Université de Lorraine, Nancy, France
Earth and Space Sciences, University of Washington, Seattle WA USA

Summary. We measured cosmogenic-ray-produced $^{21}$Ne in quartz in a 25-meter sandstone core from an extremely low erosion rate site at high elevation in the Transantarctic Mountains. Fitting a $^{21}$Ne production model to these data yields information about $^{21}$Ne production systematics.

Notable observations: Nucleogenic $^{21}$Ne and Ne thermochrometry. A significant fraction of $^{21}$Ne in these samples is the result of U and Th decay and the reaction $^{18}$O$(\alpha, n)^{21}$Ne. Fitting a production model to these data requires parameterization of this part of the $^{21}$Ne inventory as a function of the duration of nucleogenic Ne accumulation. Thus, the best-fit value of this parameter yields an Ne closure age. These rocks cooled through the Ne closure temperature (~90°C) at approx. 160 Ma.

Muon-produced $^{21}$Ne. These data require significant production of $^{21}$Ne by muon interactions. Fitting a muon production model to these data implies that most of this production is by fast muon interactions, and negative muon capture is relatively unimportant. Existing estimates of muon interaction cross-sections do a decent job of fitting the data.

What and why?

Measurements of cosmogenic $^{21}$Ne in quartz from a 25-meter sandstone core. Cosmogenic $^{21}$Ne is, in this case and in most others, measured by entirely depurating Ne from quartz samples under vacuum and then using the Ne isotope composition to determine Ne produced by cosmic-ray bombardment from atmospheric composition. This procedure, perhaps improperly, includes alpha-induced $^{21}$Ne resulting from U and Th decay.

The point is to use the depth-dependence of cosmogenic $^{21}$Ne concentrations to determine the relative importance of various $^{21}$Ne production mechanisms. We do this by fitting a production model to the data.

$^{21}$Ne production mechanisms.

Nucleogenic $^{21}$Ne. This is derived from the reaction $^{18}$O$(\alpha, n)^{21}$Ne. Nucleogenic $^{21}$Ne production depends on the U and Th concentrations (which we have measured) and the duration of time the samples have resided below the Ne closure temperature (approx. 90° C). So the nucleogenic $^{21}$Ne inventory can be parameterized by one free parameter - the Ne closure age.

Spallogenic $^{21}$Ne. The spallogenic $^{21}$Ne inventory can be specified by the surface $^{21}$Ne production rate (which we can estimate from independent calibration studies), the surface erosion rate, and an effective attenuation length $\lambda_{eff}$. The exposure age and erosion rate at this site are such that spallogenic $^{21}$Ne has not reached a steady-state production-erosion equilibrium, so an exposure time is not required. We can’t estimate both the erosion rate and the production rate simultaneously, so we specify the surface production rate.

Muon-produced $^{21}$Ne. We can compute the muon flux and energy distribution at our sample depths from the scheme of Heisinger and others, limiting three parameters that are necessary to specify the inventory of muon-produced $^{21}$Ne: $f^*$, a yield factor for negative muon capture; $\sigma_{190}$, a cross-section for fast muon interactions, and an integration time for muon production. An integration time is required because the muon decay rate at this site is such that the time required to attain production-erosion steady state for muon-produced $^{21}$Ne is well in excess of the geological constraints on the Ne closure age.

Summary. A forward model for these data requires seven parameters: Ne closure age, surface-spallogenic production rate, erosion rate, $\lambda_{eff}$, $f^*$, $\sigma_{190}$, and an integration time for production by muons. Of these, two must be specified: either the surface production rate and the erosion rate, or the muon interaction cross-sections and muon production time. There are some geological limits on some of the parameters: the Ne closure age and the muon production time can’t exceed 177 Ma (the age of basaltic dikes whose injection we consider). Anomalously low concentrations of $^{21}$Ne in some samples is probably due to high Ne diffusion rates, where the cross-section for negative muon capture has increased. Cosmogenic $^{21}$Ne concentrations do not decrease below about 1000 g cm-2, which indicates that a significant fraction of this $^{21}$Ne is in fact nucleogenic. These observations imply significant nucleogenic $^{21}$Ne concentrations - more than 10 Matoms/g for some samples.

Data fitting and what we can learn from these data.

One good fit (below and at left):

- Specified: Spallogenic $^{21}$Ne production rate (130 atoms g-1 yr-1)
- Muon integration time (15 Ma)

Results: Erosion rate 37 g cm-2 yr-1
$\lambda_{eff}$ 142.4 cm
Ne closure age 158 Ma

Negligible negative muon capture ($f^* = 0$)
$\sigma_{190}$ = 0.264 mb ($\sigma_{190} = 0.13$ atoms g-1 yr-1 at SLHL)
$\chi^2$ = 2.3

Other questions we might reasonably ask:

- Are existing estimates of muon interaction cross-sections consistent with these data? Fernandez-Mosquera et al. (GRL, 2010) estimated $f^*$ and $\sigma_{190}$ from analogue reactions. If we specify these values, we can allow the integration time for muon production to be a free parameter.

- Specified: Spallogenic $^{21}$Ne production rate (130 atoms g-1 yr-1)
- Erosion rate 37 g cm-2 yr-1
- Ne closure age 158 Ma
- Muon integration time 15 Ma (see below)

$\chi^2$ = 2.7

This results in a slightly poorer fit. The fit would be improved by reducing the integration time, but that would violate geological constraints.

How accurately have we constrained muon interaction cross-sections?

First, there is a tradeoff between the integration time we use to compute the muon-produced Ne inventory and the interaction cross-sections that we use. Because the geological limits on the integration time span an order of magnitude (15 Ma - 177 Ma), we can’t uniquely determine the cross-sections absent additional information.

Second, reasonable fits can be obtained with a broad range of muon interaction cross-sections. Here we show the best fit values obtained by specifying muon interaction parameters and allowing the integration time to be a free parameter. Again, without further constraints on the appropriate integration time, we can only weakly constraint the cross-sections.

Acknowledgements.

Core collection and some analytical work was funded by the U.S. National Science Foundation via the CRONISU-Earth project. Analytical facilities at BGC are supported in part by the Aas and Gordon Getty Foundation.