Tracing quartz through the environment

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MS received 24 December 1984

Abstract. Quartz, SiO$_2$, a pure mineral with tight crystal structure, is widespread in rocks and soil. Cosmic rays produce $^{10}$Be ($t_{1/2} = 1.5 \times 10^5$ yr) and $^{26}$Al ($t_{1/2} = 7.05 \times 10^5$ yr) in quartz exposed at or near the earth's surface. The use of accelerator mass spectrometry permits measurement of these nuclides in samples exposed at sea level for typical periods. In situ production makes interpretation relatively straightforward. Potential applications include age determination, measurement of erosion and deposition rates, and use as a tracer for continental weathering processes.

Keywords. Quartz; cosmic ray produced isotopes; erosion; accelerator mass spectroscopy.

The development of accelerator mass spectrometry (AMS) has allowed measurement of $^{10}$Be in natural materials (Brown 1984). The $^{10}$Be atoms investigated so far are those mainly produced in the atmosphere and admixed into these materials. Monaghan et al. (1983) and Pavich et al. (1984) have shown the value of this technique for soil deposition studies, but the processes involved are complex. In situ production (Jha and Lal 1981; Yiou et al. 1984), offers an attractive alternative for such studies. We discuss here the in situ production in quartz, which seems to offer several advantages.

Quartz, the common form of SiO$_2$, is an ideal target material for production of two longlived isotopes, $^{10}$Be and $^{26}$Al. Impurities, including Al, are usually present at or below a few hundred ppm. The intact crystal is impermeable to water and ions. It is abundant and easy to isolate. The two isotopes, $^{10}$Be and $^{26}$Al, are produced at rates of the order of 10 atoms/gram year at sea level, permitting a measurement in about 10 grams of quartz exposed for $10^4$ years.

The production rates of $^{10}$Be and $^{26}$Al in diverse target materials can be estimated fairly accurately (Jha and Lal 1981; Lal and Peters 1967). For a more comprehensive recent treatment, see Lal et al. (1985).

The nucleonic isotope production dominates in any material exposed at altitudes above sea level. The energy spectrum of nucleons at any given latitude remains invariant in the atmosphere at depths exceeding 200 g cm$^{-2}$, the so-called nuclear cascade equilibrium region. The depth variation of production within a rock exposed in the equilibrium region will closely follow the absorption mean free path, observed in the atmosphere. Its value varies from 150 to 170 g cm$^{-2}$, decreasing with increasing latitude, reaching a constant value for 50°–90° latitudes. The estimated production rates of $^{10}$Be and $^{26}$Al in quartz are given in table 1 for the equilibrium region at high latitudes. For lower geomagnetic latitudes, production rates in table 1 can be scaled using the latitude-altitude variation given by Lal and Peters (1967) in figure 4 for $^{10}$Be and other isotopes.
Table 1. *In situ* cosmic ray production rates of $^{10}$Be and $^{26}$Al in quartz, at geomagnetic latitudes 50°–90°

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Atmospheric pressure, $p$ (g cm$^{-2}$)</th>
<th>Nucleon spallation $^{10}$Be</th>
<th>Nucleon spallation $^{26}$Al</th>
<th>Negative mu-meson capture* $^{10}$Be</th>
<th>Negative mu-meson capture* $^{26}$Al</th>
<th>$^{10}$Be/$^{26}$Al ratio at production</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Sea level)</td>
<td>1030</td>
<td>6.5</td>
<td>21</td>
<td>6.5</td>
<td>0.236</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>925</td>
<td>15</td>
<td>48</td>
<td>10.0</td>
<td>0.258</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>730</td>
<td>63</td>
<td>210</td>
<td>22.0</td>
<td>0.271</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>550</td>
<td>$2 \times 10^2$</td>
<td>670</td>
<td>46.0</td>
<td>0.279</td>
<td></td>
</tr>
</tbody>
</table>

*Negative mu-meson capture in SiO$_2$ does not lead to production of $^{10}$Be. At depths exceeding 1000 g cm$^{-2}$ below sea level $^{10}$Be production due to nuclear interactions of fast mu-mesons becomes dominant (Jha and Lal 1981; Lal and Peters 1967). The production rate of $^{26}$Al due to negative mu-meson capture is based on procedures discussed earlier (Jha and Lal 1981; Winsberg 1956; Hampel et al 1975), that for nuclear spallation is based on published cross sections (Tobailem 1981) for formation of $^{26}$Al from proton bombardment of $^{28}$Si and the nucleon energy spectrum in the atmosphere (Lal and Peters 1967).

The slow mu-meson component attenuates with a larger absorption mean free path, $\Lambda = 245$ g cm$^{-2}$. Capture of negative mu-mesons produces $^{26}$Al ($\mu^- + ^{28}$Si $\rightarrow 2n + ^{26}$Al). $^{10}$Be is not produced by negative mu-meson capture in oxygen, but fast mu-meson coulombic interactions can produce $^{10}$Be from oxygen. At depths exceeding 1000 g cm$^{-2}$ below sea-level, production of $^{10}$Be and $^{26}$Al from fast meson interactions in SiO$_2$ becomes dominant (Jha and Lal 1981). Nucleonic production becomes unimportant at these depths. We have considered only cosmogenic production since radiogenic alphas and neutrons do not contribute to production of $^{10}$Be or $^{26}$Al in quartz.

For atmospheric depths, (200–1030) g cm$^{-2}$, isotope production rates due to capture of negative mesons can be estimated from values in table 1 using an absorption mean free path of 245 g cm$^{-2}$. At depths below sea level, the same exponent continues up to 600 g cm$^{-2}$, the absorption mean free path becomes larger at greater depths, but fast mu-meson interactions dominate.

Calculations in table 1 are based on the procedures developed earlier (Lal and Peters 1967). The energy spectrum of nucleons in the troposphere is known fairly well. Primary uncertainty arises in particular due to non-availability of the neutron excitation function for formation of $^{10}$Be from oxygen; most of the $^{10}$Be production in the troposphere is expected to occur due to neutron interactions. However, based on observations of fall-out of $^{10}$Be from the atmosphere, and also of $^{10}$Be concentrations in meteorites, one can make fairly good predictions for the $^{10}$Be production rates. This procedure has been recently adopted by Lal *et al* (1985); they obtained for the average yields of $^{10}$Be, values of 2.5, 2.2 and 1.5% respectively in nuclear disintegrations in C, N.