Cosmogenic exposure dating of glacial (and other) landforms – potentials and problems

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Outline

Basics of cosmogenic dating

Glacial exposure dating and geological uncertainties

Other cosmogenic nuclide techniques
- Burial dating
- Erosion rate quantification
Publications on cosmogenic glacial dating

ISI Web of Science search: cosmogenic AND glaci*

n = 754
Earth is constantly bombarded by cosmic rays

Interaction in the atmosphere and production of secondary cosmic rays

Production of specific cosmogenic nuclides in the earth surface
Cosmogenic nuclides produced in the earth surface when exposed to cosmic rays

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Most commonly used isotope for dating studies: $^{10}\text{Be}$
Cosmogenic isotope surface production

Cosmic rays

Production of $^{10}$Be in quartz

The production rate decrease exponentially with depth below the surface

At depths of 2-3 m or more is the production rate very low

Important for surface exposure dating
Glaciers erode!

At depths of 2-3 m or more is the production rate very low

Important for surface exposure dating

$^{10}\text{Be}$ produced in the surface is removed
At the time of deglaciation (T = 0) the $^{10}\text{Be}$ concentration is zero.

As time passes after deglaciation the sample will be exposed to cosmic ray bombardment and the $^{10}\text{Be}$ concentration will increase.
\[ T = \ln \left( 1 - N\lambda / P \right) / -\lambda \]

- \( T \) = Time (age)
- \( N \) = \(^{10}\text{Be} \) concentration
- \( \lambda \) = decay constant
  
  \[ -\ln 0.5 / 1\,387\,000 \]
- \( P \) = production rate

Sampling

Quartz separation and \(^{9}\text{Be} \) addition

AMS measurement of \(^{10}\text{Be} \)
In theory, dating of several million years old events is possible.
Also, high measurement precision has enabled dating of very young surfaces.
Ideal case

New Zealand

From Kaplan et al. (2010)
Ideal case
New Zealand

Statistics:
Arithmetic mean/1 sigma uncertainty: 11,500±330 yrs
Including production rate uncertainty: 11,500±420 yrs
Weighted mean/weighted uncertainty: 11,500±130 yrs
Peak age: 11,600 yrs
Median/Interquartile Range: 11,400±500 yrs
Reduced $\chi^2$: 1.4

From Kaplan et al. (2010)
Non-ideal case

Tibetan Plateau

From Heyman et al. (2011)
Correct age ???
Glacial exposure dating – problems

a) Ideal case

b) Prior exposure

c) Incomplete exposure
How common is prior exposure?
- in young boulders?

All boulders < 4 ka exposure age
No large prior exposure!

Heyman et al. (2011)
How common is prior exposure?  In boulders from the last deglaciation?

BIIS/FIS: Gyllencreutz et al. (2007)

Deglaciation reconstructions based on $^{14}$C dates

Independent deglaciation ages for comparison with exposure ages
More common than in young boulders but still limited

Relict boulders preserved under non-erosive ice

Glacial boulders from glacially modified landscapes

First-order process zonation

Kleman et al. (2008)
Exposure age scatter in boulders from the Tibetan Plateau

Caused by prior exposure or incomplete exposure?
Exposure age modeling (Monte Carlo model)
Incomplete exposure is typically more important than prior exposure. However, prior exposure (inheritance) does happen every now and then and cannot be ignored.
Reduced chi-square statistics:

Test if exposure age scatter can be explained by analytical uncertainty

\[ \chi^2_R = \frac{1}{n-1} \sum_{i=1}^{n} \left[ \frac{t_i - \bar{t}_i}{\sigma t_i} \right]^2 \]

Reduced \( \chi^2 \) value around 1 indicates that the entire exposure age scatter can be explained by the analytical uncertainty

Reduced \( \chi^2 \) value >2 \( \Rightarrow \) Geomorphological factors...
(Global) glacial $^{10}$Be exposure age compilation

- Tibet: 1789 samples
- Europe: 662 samples
- New Zealand: 266 samples
- North America: 835 samples
- South America: 562 samples

$\Sigma$ 4114 samples
Exposure ages

South America

North America

Europe

Tibetan Plateau

New Zealand
Reduced chisquare

Boulder sample groups
Total: 561 groups
$R_\chi^2 < 2$: 111 groups  20%

Bedrock sample groups
Total: 59 groups
$R_\chi^2 < 2$: 21 groups  36%
Reduced chi-square

**Boulder** sample groups
Total: 561 groups
$R\chi^2 < 2$: 195 groups  
**35%**

**Bedrock** sample groups
Total: 59 groups
$R\chi^2 < 2$: 26 groups  
**44%**
Error weighted mean exposure ages for groups with $R\chi^2 < 2$
Error weighted mean exposure ages for groups with $\chi^2 < 2$
Many (perhaps most) glacial exposure ages do not show the deglaciation age.

Sample groups with good clustering are mostly from the last major deglaciation in Europe.
Burial dating with multiple isotopes

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Different half-lives enables quantification of burial time (shielding from cosmic rays)
Burial dating with multiple isotopes

**Dating of Peking man**

$^{10}$Be and $^{26}$Al concentrations yield burial age of $770,000 \pm 80,000$ years

Prior estimate: $230,000 – 500,000$ years

Shen et al. (2009)

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<tr>
<th>Sample</th>
<th>$^{26}$Al $(10^6 \ \text{at}^{-1})$</th>
<th>$^{10}$Be $(10^6 \ \text{at}^{-1})$</th>
<th>$^{26}$Al/$^{10}$Be</th>
<th>Burial age (Myr)</th>
</tr>
</thead>
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<tr>
<td>Sediment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>ZKD-6</td>
<td>$0.073 \pm 0.018$</td>
<td>$0.040 \pm 0.004$</td>
<td>$1.82 \pm 0.49$</td>
<td>$2.78 \pm 0.51$</td>
</tr>
<tr>
<td>ZKD-7-2</td>
<td>$0.550 \pm 0.053$</td>
<td>$0.132 \pm 0.009$</td>
<td>$4.17 \pm 0.49$</td>
<td>$1.00 \pm 0.23$</td>
</tr>
<tr>
<td>ZKD-8/9</td>
<td>$1.252 \pm 0.095$</td>
<td>$0.273 \pm 0.008$</td>
<td>$4.58 \pm 0.38$</td>
<td>$0.75 \pm 0.16$</td>
</tr>
<tr>
<td>ZKD-10-2</td>
<td>$0.568 \pm 0.052$</td>
<td>$0.120 \pm 0.006$</td>
<td>$4.72 \pm 0.50$</td>
<td>$0.75 \pm 0.21$</td>
</tr>
<tr>
<td>ZKD-12</td>
<td>$0.105 \pm 0.030$</td>
<td>$0.021 \pm 0.006$</td>
<td>$5.10 \pm 2.01$</td>
<td>$0.62 \pm 0.74$</td>
</tr>
<tr>
<td>ZKD-13</td>
<td>$0.106 \pm 0.028$</td>
<td>$0.018 \pm 0.005$</td>
<td>$5.89 \pm 2.35$</td>
<td>$0.31 \pm 0.74$</td>
</tr>
<tr>
<td>Artefacts (8/9)</td>
<td></td>
<td></td>
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<td>ST-1</td>
<td>$0.199 \pm 0.027$</td>
<td>$0.040 \pm 0.002$</td>
<td>$4.95 \pm 0.72$</td>
<td>$0.67 \pm 0.29$</td>
</tr>
<tr>
<td>ST-2</td>
<td>$0.476 \pm 0.037$</td>
<td>$0.100 \pm 0.003$</td>
<td>$4.77 \pm 0.39$</td>
<td>$0.73 \pm 0.17$</td>
</tr>
<tr>
<td>ST-3</td>
<td>$0.371 \pm 0.039$</td>
<td>$0.122 \pm 0.003$</td>
<td>$3.04 \pm 0.33$</td>
<td>$1.66 \pm 0.21$</td>
</tr>
<tr>
<td>ST-4</td>
<td>$0.568 \pm 0.083$</td>
<td>$0.120 \pm 0.005$</td>
<td>$4.72 \pm 0.71$</td>
<td>$0.75 \pm 0.29$</td>
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Burial dating with multiple isotopes

Quantification of burial under ice

600 000 years burial under ice

Stroeven et al. (2002)

$79 \pm 17 \text{ ka}$

$64 \pm 14 \text{ ka}$

$37 \pm 8 \text{ ka}$
Erosion rate quantification

Bierman and Caffee (2001)
Namib desert

Bedrock samples
Catchment-scale erosion rate quantification

Average catchment-scale erosion rates quantified based on river sediments

von Blanckenburg (2005)
Catchment-scale erosion rate quantification
Catchment-scale erosion rate quantification
Summary

• Cosmogenic dating is easy to apply because rocks (quartz) are everywhere (common)
• It requires much lab work (expensive)
• Cosmogenic dating can give an absolute measurement of exposure to cosmic rays
• To convert exposure to cosmic rays into an age we have to make several crucial assumptions regarding the exposure history
Thank you!