Brief history of cosmogenic nuclides

- 1911 - First cosmic ray measurements: Hess
- 1927 - Cosmic rays contained charged particles: Skobeltzyn
- 1937 - Discovery of $^{14}$C at Berkeley: Ruben and Kamen
- 1939 - Prediction of $^{14}$N(n,p) $^{14}$C reactions in the atmosphere: Korff and Danforth
- 1947 - Prediction of $^{3}$He production in iron meteorites: Baur
- 1949 - First measurement of natural $^{14}$C: Chicago group
- 1951 - Publication of first $^{14}$C dates: Arnold and Libby
Brief history of cosmogenic nuclides

- 1952 - Detection of cosmic-ray-produced $^3$He in iron meteorites: Paneth, Reasbeck, and Mayne
- Cosmogenic nuclides have been used to study the exposure history of the Canyon Diablo iron meteorite
- Berringer crater is the site of the early terrestrial cosmogenic nuclide calibrations
Cosmic rays produce a variety of nuclides in the solar system - meteorites
Cosmogenic nuclides - planetary surfaces
Cosmic rays produce a variety of nuclides on the Earth’s surface
Production of terrestrial cosmogenic nuclides
## Cosmogenic Nuclides

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Half-life (yr)</th>
<th>Main Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$H</td>
<td></td>
<td>All elements</td>
</tr>
<tr>
<td>$^3$He</td>
<td>12.3</td>
<td>Stable All elements</td>
</tr>
<tr>
<td>$^{10}$Be</td>
<td>1.5 x 10$^6$</td>
<td>C, O</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>5730</td>
<td>Mg, Al, Si</td>
</tr>
<tr>
<td>$^{21}$Ne, $^{22}$Ne</td>
<td>Stable</td>
<td>Si, Al</td>
</tr>
<tr>
<td>$^{26}$Al</td>
<td>7.1 x 10$^5$</td>
<td>Ca, K, Fe, Cl</td>
</tr>
<tr>
<td>$^{36}$Cl</td>
<td>3.0 x 10$^5$</td>
<td>Fe, Ca, Cl</td>
</tr>
<tr>
<td>$^{36}$Ar, $^{38}$Ar</td>
<td>Stable</td>
<td>Ca, Fe</td>
</tr>
<tr>
<td>$^{41}$Ca</td>
<td>1.0 x 10$^5$</td>
<td>Fe</td>
</tr>
<tr>
<td>$^{53}$Mn</td>
<td>3.7 x 10$^6$</td>
<td>Ni</td>
</tr>
<tr>
<td>$^{59}$Ni</td>
<td>7.6 x 10$^4$</td>
<td>Rb, Sr, Zr</td>
</tr>
<tr>
<td>$^{81}$Kr</td>
<td>2.3 x 10$^5$</td>
<td>Te, Ba, La</td>
</tr>
<tr>
<td>$^{129}$I</td>
<td>1.6 x 10$^7$</td>
<td></td>
</tr>
</tbody>
</table>
Radio-isotope abundance ratios

Decay counting  
AMS

Conventional mass spectrometry
AMS at Purdue
How does AMS differ from conventional MS?

- High abundance sensitivity
  - Multiple stages of momentum, velocity, and electrostatic analysis
- Molecular species generally eliminated via stripping
  - $^{14}\text{C}:^{12}\text{C}^1\text{H}_2^{+q},^{12}\text{C}^{16}\text{O}^{+2q}$
  - $^{36}\text{Cl}:^{1}\text{H}^{35}\text{Cl}$
- Particle energies allow $dE/dx$ techniques to be utilized
  - $^{10}\text{B}$ is separated from $^{10}\text{Be}$ by an absorbing foil
  - $^{36}\text{S}$ is distinguished from $^{36}\text{Cl}$ by $dE/dx$ in the detector
AMS requires the production of a negative ion.
Negative ion production enables the measurement of $^{14}\text{C}$ and $^{26}\text{Al}$
AMS at Purdue
The stripper at the accelerator terminal suppresses molecular interferences.
$^{41}\text{CaF}_3^-$ MeV 76 MeV $^{41}\text{Ca}^{8+}$ energy loss spectra

$^{41}\text{Ca} / ^{40}\text{Ca} = 10^{-9}$ Standard

Blank sample

Ion energy lost in 1$^{st}$ half of detector

Ion energy lost in 2$^{nd}$ half of detector
The Purdue Rare Isotope Measurement Laboratory (PRIME Lab)

- Purdue University is home of the only university-based accelerator-mass-spectrometry (AMS) multi-isotope facility in the United States
- PRIME Lab has facilities support from the NSF geosciences program and facilities upgrade funds from NASA

Measurements performed at PRIME Lab enable Purdue research endeavors and research activities from numerous research groups outside Purdue University
The ability to measure cosmogenic or tracer radionuclides has opened new fields of research

- Traditional Geoscience
  - Extraterrestrial studies
  - Landscape evolution
  - Atmospheric sciences
  - Hydrologic science
- Environmental Science
  - Radionuclide migration
  - Transport and fate of toxins
- Archaeology
- Biomedical Science

The list of applications is long and growing
Cosmogenic nuclides - present and future

- Cosmogenic nuclides have been used extensively to determine exposure age histories for extra-terrestrial materials
- A relatively new application is terrestrial exposure age dating
  - Many studies have amply demonstrated desirability of this method
  - Nevertheless, there are numerous complications in this application
- Previous experience with extraterrestrial material points the way to advances possible in the terrestrial setting
Goals of Cosmogenic Nuclide Measurements in WAIS Divide Core

- Establish a chronological link between the WDC06 core to the Greenland cores (GISP2, NGRIP, NEEM) and to the Holocene $^{14}$C tree-ring record.
- Investigate possible links between climate and solar activity: is cosmogenic $^{10}$Be a reliable measure of the Total Solar Irradiance (TSI)?
- Determine paleo-accumulation rate (last glacial period).
- Better characterize long-term atmospheric mixing models
WAIS Divide ice core

- Low-resolution core (0-560m)
  - Waste samples of 1-2 kg were collected from the continuous ice core melter at the Desert Research Institute (DRI)
  - A typical $^{10}$Be sample represents ~3 m of ice core and 12 years of snow accumulation
  - Two samples were combined for $^{36}$Cl analysis
    - We assumed an average Cl of 43±10 ppb (which is 5-10% of total Cl)

- High resolution core (0-114m)
  - We are measuring $^{10}$Be from annual layers
  - Each sample is 100-300 g of ice
$^{10}\text{Be}$ concentration in WDC06A

$^{10}\text{Be}$ in WAIS Divide

Time (calendar years C.E., Timescale WDC06A:1)
$^{10}\text{Be flux} = ^{10}\text{Be} \times \text{SAR (cm weq/yr)}$

Graph showing the correlation between $^{10}\text{Be}$ flux, $^{10}\text{Be}$ concentration in ice, and age over the years CE. The graph indicates periods labeled as O, W, S, M, and D, possibly indicating specific events or phases in the study.
Variations in $^{10}\text{Be}$ on 10 and 100 year timescales
$^{10}$Be in WDC06A and GISP2 cores

**Graph:**
- **Y-axis:** $^{10}$Be ($10^3$ at/g ice)
- **X-axis:** Time (calendar years C.E., Timescale WDC06A:1)

**Legend:**
- **GISP2**
- **WAIS Divide**

**Key Events:**
- O, W, S, M, D

**Notes:**
- The graph shows the concentration of $^{10}$Be in two ice cores over time.
10Be in WDC06A and Dome Fuji

Age (calendar years CE, Timescale WDC06A-1)
$^{10}\text{Be}$ and $^{36}\text{Cl}$ in WDC06A

$^{36}\text{Cl} \ (1.72 \times 10^3 \ \text{at/g})$

$^{10}\text{Be} \ (13.2 \times 10^3 \ \text{at/g})$

Deviation from average (%)

Time (Calendar years C.E., Timescale WDC06A-1)
$^{10}\text{Be}/^{36}\text{Cl}$ in WDC06A

$^{10}\text{Be}/^{36}\text{Cl} = 7.7 \pm 0.9$
$^{10}$Be in WDC06A vs. $^{14}$C tree-ring record

![Graph showing the comparison of $^{10}$Be and $^{14}$C records over time.]

- X-axis: Time (calendar years C.E., Timescale WDC06A:1)
- Y-axis left: delta-$^{10}$Be (%)
- Y-axis right: delta-$^{14}$C (‰)

The graph illustrates the historical variations in $^{10}$Be and $^{14}$C records over time.
WAIS Divide and GISP2 concentrations – 3 year averages
$^{10}\text{Be}$ concentration and sunspot number?
TSI vs. $^{10}\text{Be}$ in WAIS Divide

We need to compare the TSI for the last 30 years with the annual $^{10}\text{Be}$ record.
Cosmogenic nuclide concentrations: nuclear physics parameters and controlling geologic factors

\[
N(z,t) = \left[ N(z,0)e^{-\lambda t_e} + \frac{P(t)}{\lambda + \mu \varepsilon} e^{-\mu z} (1 - e^{-(\lambda + \mu \varepsilon) t_e}) \right]
\]

\[
\mu = \frac{\rho}{\Lambda}
\]

\[
N(z,0) = \text{concentration at depth, } z, \text{ when } t_e = 0
\]

\[
P = \text{production rate (latitude and elevation dependent)}
\]

\[
\mu = \text{absorption coefficient for cosmic rays}
\]

\[
\Lambda = \text{interaction mean free path}
\]

\[
\varepsilon = \text{erosion rate}
\]

\[
t_e = \text{exposure time}
\]
The measured concentration of a cosmic-ray produced radionuclide is controlled by several geologic factors.

\[ N(z, t) = \left[ N(z, 0)e^{-\lambda t_e} + \frac{P(t)}{\lambda + \mu \varepsilon} e^{-\mu z} \left(1 - e^{-(\lambda + \mu \varepsilon) t_e}\right) \right] \]

<table>
<thead>
<tr>
<th>Geologic Process</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most recent duration of exposure to cosmic rays</td>
<td>( t_e )</td>
</tr>
<tr>
<td>Depth of sample during this exposure</td>
<td>( z )</td>
</tr>
<tr>
<td>Duration of earlier exposure</td>
<td>( N(z, 0) )</td>
</tr>
<tr>
<td>Erosion rate</td>
<td>( \varepsilon )</td>
</tr>
</tbody>
</table>
Exposure age dating - ideal case

\[ N(z,t) = \left[ N(z,0)e^{-\lambda t} + \frac{P(t)}{\lambda + \mu \epsilon}e^{-\mu z}(1 - e^{-(\lambda + \mu \epsilon) t}) \right] \]

\[ N(z,0) = 0 \]
\[ \epsilon = 0 \]
\[ z = 0 \text{ or is known} \]

\[ N(z,t) = \frac{P(t)}{\lambda}(1 - e^{-\lambda t}) \]
Systematics of terrestrial production

(from Lal, 1991 and Nishiizumi et al., 1991)
Systematics of terrestrial production

- Exposure ages $> 10^5$ yr require low erosion rates
- Long exposure ages and low erosion rates are best attained in arid conditions

(from Lal, 1991 and Nishiizumi et al., 1991)
Cosmogenic nuclides from the Atacama Desert

(Data and figures taken from Nishiizumi et al., 237, EPSL, 2005)
Cosmogenic exposure ages and erosion rates

<table>
<thead>
<tr>
<th>ID</th>
<th>Minimum $^{10}\text{Be}$ Exp Age (Myr)</th>
<th>Maximum Erosion Rate (m/Myr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>0.35±0.01</td>
<td>1.68±0.05</td>
</tr>
<tr>
<td>18</td>
<td>0.33±0.01</td>
<td>1.80±0.04</td>
</tr>
<tr>
<td>19</td>
<td>0.32±0.01</td>
<td>1.93±0.09</td>
</tr>
<tr>
<td>20</td>
<td>0.10±0.01</td>
<td>6.03±0.15</td>
</tr>
<tr>
<td>21</td>
<td>2.22±0.05</td>
<td>0.17±0.02</td>
</tr>
<tr>
<td>22</td>
<td>2.63±0.06</td>
<td>0.10±0.03</td>
</tr>
<tr>
<td>23</td>
<td>3.49±0.24</td>
<td>0.06±0.02</td>
</tr>
<tr>
<td>24</td>
<td>3.08±0.19</td>
<td>0.12±0.04</td>
</tr>
<tr>
<td>72</td>
<td>0.36±0.01</td>
<td>1.67±0.04</td>
</tr>
<tr>
<td>73</td>
<td>1.14±0.03</td>
<td>0.36±0.09</td>
</tr>
<tr>
<td>74</td>
<td>4.41±0.29</td>
<td>0.03±0.01</td>
</tr>
<tr>
<td>251</td>
<td>0.34±0.01</td>
<td>1.67±0.04</td>
</tr>
</tbody>
</table>

(Data and figures taken from Nishiizumi et al., 237, EPSL, 2005)
Cosmogenic $^{21}\text{Ne}$ from the Atacama Desert

(Data and figures from Dunai et al., 33 Geology 2005)
First order observations

- Cosmogenic nuclide measurements of cobbles from the Atacama Desert demonstrate a Miocene age for these landscapes
- Maximum erosion rates are $< 0.1$ m/Myr from cobbles taken from alluvial fans
- Bedrock erosion rates are $\sim$ an order of magnitude higher than cobble erosion rates
- Although cobbles have long exposure histories they are not necessarily simple exposure histories
Complex exposure histories

\[ N(z,t) = \left[ N(z,0) e^{-\lambda t_e} + \frac{P(0)}{\lambda + \mu \varepsilon} e^{-\mu z} \left(1 - e^{-(\lambda + \mu \varepsilon)t_e}\right) \right] e^{-\lambda t_b} \]

(Data and figures taken from Nishiizumi et al., 237, EPSL, 2005)
Lamb and Davis (Nature, 425, 2003) propose that the dynamics of subduction and mountain building are controlled by the availability of erosion.

Dunai et al (Geology, 33, 2005) note that low erosion rates in the Atacama Desert have been prevalent for ~ 25 Myr.
Cosmogenic nuclides in arid environments

- Cosmogenic nuclides are readily measured from arid and hyper-arid environments
- These environments are ideal testing grounds for cosmogenic nuclides
- These measurements unequivocally demonstrate the antiquity of landforms
- Ages and erosion rates determined using cosmogenic nuclides in turn are being used to reconstruct climate change chronologies and understand relationships between climate change and tectonic activity
Exposure ages of boulders across the Himalaya and Tibet

- Cosmogenic nuclide exposure ages do not always yield well-defined ages for individual landforms.
- Does the minimum age or maximum boulder age best represent the moraine age?
- What geologic processes account for the spread in ages?
Glacial cycles in Hunza

Moraines of different Glacial Stages (after Derbyshire et al. 1994):
- 18. Pasu II (youngest)
- 17. Pasu I
- 16. Batura
- 15. Ghulkin II
- 14. Ghulkin I
- 13. Borti Jheel
- 12. Yung
- 11. Sainc (oldest)

Landforms
- Glacier
- River and floodplain
- Litts
- Streets
- Borti Jheel (Lake)
- Glacial deposits
- Glaciated bedrock surfaces (Borti Jheel and Sainc Stages)

Timelines:
- None
- 139±23 kyr
- 50-65 kyr
- 47±3 kyr

None

300-900 yr

Historical

Ghulkin Glacial Stage (15)
Batura Glacial Stage (16)
Pasu I Glacial Stage (17)
Pasu II Glacial Stage (18)
Glacial cycles in Hunza
Ladakh glacial chronologies

(Owen et al, 2005)
Ladakh glacial moraines

(Owen et al, 2005)
Ladakh glacial chronology

(Owen et al, 2005)
Post-glacial shielding by boulder exhumation

Numerical model assuming constant boulder exhumation (5 cm/ka) through till (2.0 g/cm³, 165 g*cm⁻²)

Extreme age step

MODELLED EXPOSURE AGE DATA

n = 2440

Older samples → wider age spread

MEASURED EXPOSURE AGE DATA

20-point running mean
Cosmogenic nuclides can be used to study large-scale tectonics.
Cosmogenic nuclides can be used to study large-scale tectonics

- There is considerable disparity between cosmogenic-nuclide-based slip rates and geodetic-based slip rates - the latter are less
Burial times and pre-burial erosion rates can be inferred

![Graph showing 26Al/10Be ratio vs. [10Be] (atoms/gram) with lines indicating erosion and exposure rates.](image)
Australopithecus fossils at Sterkfontein, South Africa
AMS at Purdue