Terrestrial cosmogenic isotopes

Great impact on environmental and earth sciences over the last decade

Methodological process is accelerating

Many novel tools

Cockburn & Summerfield 2004
Große Naturkatastrophen 1950 – 2007
Anzahl der Ereignisse

Anz.
16  Erdbeben, Tsunami, Vulkanausbruch
14  Sturm
12  Überschwemmung
    Temperaturextreme
    (z. B. Hitzewelle, Waldbrand)

Quelle: Münchener Rückversicherungs-Gesellschaft GeoRisikoForschung, NatCatSERVICE; Stand: Jan. 2008
Terrestrial cosmogenic isotopes

The “centre of mass” of many geoscience departments has shifted from solid Earth subfields towards surface processes (Bruce Watson, Elements 2009)

Cockburn & Summerfield 2004

Davis et al. 2003: papers containing “U-Pb” and “zircon” as key words
Improvements: particle accelerators instead of counting

AMS has a factor of a million lower detection limit for $^{14}\text{C}$, $^{36}\text{Cl}$, $^{10}\text{Be}$, $^{26}\text{Al}$ compared to counting methods
Why studying cosmogenic isotopes?

Understanding the geological evolution of the Earth surface

Landscape dynamics (e.g. erosion rates) on the million year time scale

Variation of solar radiation

Ocean circulation

Dating of Holocene climate changes
Discovery of cosmic-rays

Libby introduced radiocarbon dating ($^{14}$C) in 1947 (received Nobel Prize in chemistry in 1960)

Discovery of $^{10}$Be, $^{7}$Be (1956-1957)
Arnold (Chicago)
Peters, Devendra Lal (Bombay)

Victor Hess discovered the „cosmic rays“ in his balloon flights of 1911-1912 (received Nobel Prize in physics in 1936)
Galactic cosmic rays: originate in sources outside the solar system, throughout our Milky Way galaxy.

Solar energetic particles: nuclei and electrons accelerated in association with energetic events on the Sun.

Galactic cosmic rays derive their energy from supernova explosions
Crab nebula (Krebsnebel)
The light elements Li, Be and Bor (skipped by nucleosynthesis) are produced by cosmic rays (Walker et al. 1985)

3-alpha process

\[
\frac{4}{2} \text{He} + \frac{4}{2} \text{He} \rightarrow \frac{8}{4} \text{Be} \\
\frac{8}{4} \text{Be} + \frac{4}{2} \text{He} \rightarrow \frac{12}{6} \text{C} + \gamma
\]
Energy of cosmic-rays

Components of galactic cosmic-rays
- 87-89% protons
- 10-12% $\alpha$-particles
- 1-2% electrons
- 1% heavier elements

Secondary cosmic-rays
- Pions $\rightarrow$ muons, neutrinos, $\gamma$-rays
- electrons
- positrons

Particle colliders
- Tevatron, Fermilab, USA
- LHC, CERN, Geneva
When the sun is active, we get fewer cosmic rays here.

What about long-term averaged intensity variation in the Earth's magnetic field?
The **rate of production** of cosmogenic isotopes depends on the concentrations of the target elements (O, K, Ca, Mg), elevation, surface orientation, and geomagnetic latitude.

**Comparison with redness of a person’s skin (suntan)**

*Gosse and Phillips (2001)*

- Suntan – wears away
- Cosmogenic nuclide – decays

- Suntan lotion shields skin from radiation
- Atmosphere and snow shields a landform from radiation

- Not everybody tans to the same degree of redness
- Nuclide production varies in different minerals
Cosmic rays protons interact with nuclei in the upper atmosphere, producing neutrons which in turn interact with atmosphere and rock surface.
A. $^{14}\text{C}$ created by neutron capture

Proton Neutron

$^{14}\text{N}$

$7p + 7n$

Proton expelled

$^{14}\text{C}$

$6p + 8n$

B. $^{14}\text{C}$ decays to $^{14}\text{N}$ by $\beta^-$ decay

$^{14}\text{C}$

$6p + 8n$

$\beta^-$ Particle

$^{14}\text{N}$

$7p + 7n$
Terrestrial cosmogenic isotopes

Basic applications

1. Dating via radioactive decay
2. Dating via nuclide accumulation
3. Exchange rate quantification via nuclide accumulation and extraction
4. Nuclide concentrations as function of paleomagnetic and solar intensity
### Production of cosmogenic isotopes

**Major in-situ produced cosmogenic nuclides in terrestrial materials**

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Production rate (atoms / g / year)</th>
<th>Half-life (years)</th>
<th>Target elements in terrestrial rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$He</td>
<td>75 – 100 (olivine)</td>
<td>stable</td>
<td>O, Si, Al, Mg</td>
</tr>
<tr>
<td>$^{10}$Be</td>
<td>5 – 7 (quartz)</td>
<td>$1.5 \times 10^6$</td>
<td>O, Si, Al, C</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>18 – 20</td>
<td>5730</td>
<td>C, O</td>
</tr>
<tr>
<td>$^{21}$Ne</td>
<td>18 – 21 (quartz)</td>
<td>stable</td>
<td>Mg, Na, Si, Al</td>
</tr>
<tr>
<td>$^{26}$Al</td>
<td>30 – 36 (quartz)</td>
<td>$0.71 \times 10^6$</td>
<td>Si, Al</td>
</tr>
<tr>
<td>$^{36}$Cl</td>
<td>8 – 10 (basalt)</td>
<td>$0.30 \times 10^6$</td>
<td>Cl, K, Ca</td>
</tr>
<tr>
<td>$^{53}$Mn</td>
<td>?</td>
<td>$3.7 \times 10^6$</td>
<td>Fe</td>
</tr>
</tbody>
</table>

*Cerling & Craig (1994) Annu. Rev. Earth Planet. Sci. 22*

**Major target minerals:**
- $^3$He: olivine, pyroxene hornblende
- $^{10}$Be, $^{14}$C, $^{21}$Ne, $^{26}$Al: quartz
- $^{36}$Cl: calcite, K-feldspar

Cosmogenic isotopes are produced in near surface rock by collisions of high energy neutrons and muons with specific target elements in rocks and minerals. All production rates scaled to sea-level high latidude (>60°)
<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$T_{1/2}$ y</th>
<th>$\lambda$ y$^{-1}$</th>
<th>Principal Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{10}$Be</td>
<td>$1.5 \times 10^6$</td>
<td>$0.462 \times 10^{-6}$</td>
<td>Dating marine sediment, Mn-nodules, glacial ice, quartz in rock exposures, terrestrial age of meteorites, and petrogenesis of island-arc volcanics</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>$5730 \pm 40$</td>
<td>$0.1209 \times 10^{-3}$</td>
<td>Dating of biogenic carbon, calcium carbonate, terrestrial age of meteorites</td>
</tr>
<tr>
<td>$^{26}$Al</td>
<td>$0.716 \times 10^6$</td>
<td>$0.968 \times 10^{-6}$</td>
<td>Dating marine sediment, Mn-nodules, glacial ice, quartz in rock exposures, terrestrial age of meteorites</td>
</tr>
<tr>
<td>$^{32}$Si</td>
<td>$276 \pm 32$</td>
<td>$0.251 \times 10^{-2}$</td>
<td>Dating biogenic silica, glacial ice</td>
</tr>
<tr>
<td>$^{36}$Cl</td>
<td>$0.308 \times 10^6$</td>
<td>$2.25 \times 10^{-6}$</td>
<td>Dating glacial ice, exposures of volcanic rocks, groundwater, terrestrial age of meteorites</td>
</tr>
<tr>
<td>$^{39}$Ar</td>
<td>269</td>
<td>$0.257 \times 10^{-2}$</td>
<td>Dating glacial ice, groundwater</td>
</tr>
<tr>
<td>$^{53}$Mn</td>
<td>$3.7 \times 10^6$</td>
<td>$0.187 \times 10^{-6}$</td>
<td>Terrestrial age of meteorites, abundance of extraterrestrial dust in ice and sediment</td>
</tr>
<tr>
<td>$^{59}$Ni</td>
<td>$8 \times 10^4$</td>
<td>$0.086 \times 10^{-4}$</td>
<td>Terrestrial age of meteorites, abundance of extraterrestrial dust in ice and sediment</td>
</tr>
<tr>
<td>$^{81}$Kr</td>
<td>$0.213 \times 10^6$</td>
<td>$3.25 \times 10^{-6}$</td>
<td>Dating glacial ice, cosmic-ray exposure age of meteorites</td>
</tr>
</tbody>
</table>