Thermochronology, cosmogenic isotopes and dating of young sedimentary rocks

Part 7: K/Ar, Ar/Ar, Luminescence, ESR and Cosmogenic dating of sediments

István Dunkl

http://www.sediment.uni-goettingen.de/staff/dunkl/

Intro: Where are the geotherms?
Geothermometry in basins by: vitrinite reflectance, bitumen refl.,
  graptolite refl., Raman spectroscopy, conodont alteration,
  spore colour, fluorescence, Rock-Eval, clay mineralogy

Let's start the dating work: research concept, mineral separation

Fission track dating:  - nuclear physics
  - age equation, statistics
  - track lengths

Volcanic events (= formation ages)
Basement exhumation (= cooling ages)
Complex T histories of basins & thermal modelling
Detrital chronology (provenance by single-grain ages)

(U-Th)/He thermochronology

K/Ar, Ar/Ar, Luminescence, ESR and Cosmogenic dating of sediments
U/Pb and U/Th dating of sediments
K/Ar and Ar/Ar dating in sedimentary environment
- detrital feldspar grains
- Fp authigenic overgrowth
- illite neoformation

Luminescence
Electron spin resonance
Cosmogenic dating
Ar/Ar dating ---- what is usually expected is a “nice” plateau

[Münch et al., 2006]
Figure 3.7: Age spectra and K/Ca ratios (left) and Arrhenius plots (right) for alkali feldspar samples from the Gascoyne region.
Ar/Ar dating

Figure 4.3: Monotonic thermal history models calculated with the Lovera FORTRAN codes for K-feldspar samples from the eastern Pilbara Craton. Dark grey area in the thermal history models indicate 90% confidence interval of all individual cooling histories (N≥20), light grey represents 90% confidence interval of the mean.
Authigenic feldspar dating by laser Ar/Ar + pT constraints by fluid inclusions

Figure 2. A: Transmitted-light photomicrograph showing reservoir sample from well 204/28–1. Arrows indicate authigenic K-feldspar overgrowths enveloping heavily altered grains of plagioclase. PS is pore space stained blue. B: Backscattered-electron scanning electron microscope photomicrograph showing authigenic K-feldspar overgrowths (white arrow) and authigenic quartz overgrowths (black arrow) enveloping detrital feldspar (DF) and detrital quartz (DQ) grains. White box shows site from which focused ion beam–
Ar/Ar dating with fluid inclusion studies

[Mark et al., 2005]
K/Ar dating of diagenetic illite

[Hamilton et al., 1992]
**K/Ar dating of diagenetic illite**

Fig. 4. TEM photographs of extreme grain size-fractions of Zempleni sample (sedimented on a carbon-coated copper grid, 10,000 × magnification). Aggregates occur in the coarse fraction (B) and fundamental particles in the fine fraction (A). The bars in the right bottom corner of the photos represent 0.1 μm.

[Clauer et al., 1997]
K/Ar dating of diagenetic illite

Fig. 2. XRD patterns of oriented and glycolated preparations of different grain fractions of sample CIC1/20, illustrating the increase of expandability (%S), i.e. decrease of the thickness of fundamental particles in fine fractions. Note intensity scale change at 29° × 20°; Co-Kα radiation.

[Clauer et al., 1997]
Fig. 3. Illustration of the effect of decreasing fundamental particle thickness and mixed-layer crystal thickness on XRD expandability ($%S_{XRD}$) which is defined as the ratio of smectitic interlayers (empty) to smectitic plus illitic (black dots) interlayers inside crystals, decreases with decreasing mixed-layer crystal thickness (compare A and B) but increases with decreasing fundamental particle thickness $T$ (compare C and A).
K/Ar dating of diagenetic illite

Figure 14. Effect of downward-moving oil-water contact on the apparent age of diagenetic illite that is growing at the time of oil emplacement. Displacement of water by accumulating oil causes cessation of illite growth and younger illite at structurally lower levels.

Figure 15. Apparent potassium/argon ages of diagenetic illite (less than 0.1 μm fraction) in the Brent Sandstone at Heather field. Decreasing age with depth is interpreted to be the result of gradual accumulation of oil and consequent displacement of water within the structure. Data from well 2/5-9 reflect a different diagenetic history from the main field.
K/Ar dating of diagenetic illite

Fig. 10. Migration of hydrocarbons through Brent Group. Schematic cartoon illustrating the effect of fluid flow being preferentially focused at the time of hydrocarbon migration by overall permeability contrast between the ‘clean’ Etive sands and the ‘dirtier’ sands of other Brent Formations.

[Hamilton et al., 1992]
K/Ar dating of diagenetic illite

Fig. 6. Burial histories of the East Slovak Basin reconstructed for the Trhoviste-1 and Cicarovce-8 borehole data. The burial histories of the studied samples are shown (for CIC1/20 sample, the Cicarovce-8 model, which is the closest available, was used). The bentonite K-Ar ages (from Table 1) and estimated periods of shale and bentonite illitization (see text) are also shown.

[Clauer et al., 1997]
K/Ar dating of diagenetic illite

Fig. 9. Plot of calculated time at which $R_0$ in overlying Kimmeridge Clay Formation source rock reached 0.62% versus K-Ar age of finest illite separate. The solid diagonal line represents 1:1 correlation of the $x$, $y$, axes.

[Hamilton et al., 1992]
K/Ar dating of illites in Brent Group reservoirs

[Hamilton et al., 1992]
Luminescence dating

Several non-conducting materials adsorb radiation energy.

The electrons get higher energetic level, but this is a metastable state, heat, VIS or IR irradiation set the electrons to the normal energetic level, and the adsorbed energy is irradiated: a photon is released.

This process makes visible light. The intensity of the light is proportional to the environmental radioactivity and the accumulation time (since sedimentation).

\[
\text{Luminescence age (a)} = \frac{\text{Palaeodose (Gy)}}{\text{Dose rate (Gy a}^{-1})}
\]
Luminescence dating

Typical infrared stimulated luminescence color images (IRSL-CIs) from granite and microcline slices. Real surface images, (A) and (D), are from granite (HW-2) and microcline (India) slices, respectively. Two yellowish IRSL-CIs, (B) and (E), were photographed in visible light regions by interpolating a filter (CF 50E) between camera and slice sample, under illumination by infrared light from LED. Two reddish IRSL-CIs, (C) and (F), were photographed by interpolating an additional filter (R-60). Both slices were irradiated with X-rays to a dose of 200Gy and left for more than one day before photography.

[Hashimoto et al., 2003]
Principle of luminescence dating

[Preusser et al., 2008]
Luminescence dating
acummulation and belaching of luminescence signal through the geological gistory of grains in a sediment

[Bailey and Arnold, 2006]
Figure 2. Diagrammatic representation of the TL geological cycle. Light exposure reduces the TL signal of sediment to a low definable level. After burial of the sediment ionizing radiation progressively imparts a TL signal. The TL signal at the time of collection is termed the natural TL. Beta doses added to the natural TL signal defines a function, which is often the basis for determining the equivalent dose. Modified from Wintle and Huntley, 1982.
Luminescence dating

Figure 5  The effect of sunlight exposure on OSL (using 514 nm laser line) and TL signals from some geologically old quartz and feldspar samples. (After Godfrey-Smith et al., 1988). Robertson et al. (1991) have shown that optical bleaching rates of TL vary among feldspar types: intermediate composition (K-Na) feldspars bleach more rapidly than high-K and high-Na feldspars.
Luminescence dating

Figure 4. (A) Schematic representation of apparatus for thermoluminescence measurement (from Aitken, 1985a, p. 5, fig. 1.2). Reprinted from Nuclear Tracks and Radiation Measurements with kind permission from Elsevier Science Ltd. (B) Design of a variable narrow bandpass optically stimulated luminescence system (from Pierson and others, 1994; fig. 1). Reprinted from Radiation Measurements with kind permission from Elsevier Science Ltd.

[Forman et al., 2000]
Luminescence dating

Figure 4  Typical luminescence decay curves from quartz and feldspar extracts using the Ar-ion laser line at 514 nm for stimulation. (After Godfrey-Smith et al., 1988).

[Berger, 1995]
Luminescence dating

Figure 1. (A) Plot of the thermoluminescence emission spectrum for irradiated large grains of potassium feldspar (from Rendell and others, 1993, fig. 1). The TL signal of mineral grains is three dimensional, with the intensity of light emission dependent on temperature and wavelength. (B) Standard TL emission curves for various wavelengths derived from emission spectra in Figure 1A.

[Forman et al., 2000]
**Luminescence dating**  
Additive-dose response curve. Different laboratory doses are added to the natural signal (NL) to characterise the increase of luminescence intensity with dose.

\[
\text{Luminescence age (a)} = \frac{\text{Palaeodose (Gy)}}{\text{Dose rate (Gy a}^{-1}\text{)}}
\]

\((\text{Gy/gray} = 1 \text{ J/kg})\)

[Preusser et al., 2008]
Luminescence dating of a meander

[Duller, 2008]
Luminescence dating of dunes

Fig. 2. Composite form and episodic accumulation of a Namib linear dune (after Bristow et al. 2007).

[Lancaster, 2008]
Luminescence dating

Figure 3. Diagrammatic representation of the most appropriate sediments to sample for luminescence dating in normal faulted terrain. Previous research indicates that fine-grain facies of distal colluvium, buried A horizon silt, and certain sag pond muds yield apparently accurate thermoluminescence age estimates.

[Forman et al., 2000]
Luminescence dating

Figure 16  TL age versus independent age for the fine-silt, polymineralic fraction of loess samples from New Zealand and Alaska (after Berger et al., 1992, 1994). The extrapolation methods are those of Figure 9a.
### Luminescence dating

<table>
<thead>
<tr>
<th>Factor</th>
<th>Effect on Luminescence Age Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inadequate compensation for partial solar resetting of the luminescence signal</td>
<td>Overestimate in age by 10 to 200 percent</td>
</tr>
<tr>
<td>Inadequate compensation for non-linearity in luminescence growth function</td>
<td>Overestimate in age by 10 to 100 percent</td>
</tr>
<tr>
<td>Anomalous fading</td>
<td>Underestimate in age by 5 to 50 percent</td>
</tr>
<tr>
<td>Uncertainty in moisture content</td>
<td>Decrease in precision by 10 to 40 percent</td>
</tr>
<tr>
<td>Disequilibrium in U and Th decay series</td>
<td>Variable, over or underestimate by 5 to 50 percent</td>
</tr>
<tr>
<td>Non-analogous response to laboratory irradiation, due to sensitivity change</td>
<td>Variable but could result in underestimates by &gt;25 percent</td>
</tr>
</tbody>
</table>

[Forman et al., 2000]
Electron Spin Resonance

Figure 1. Energy band scheme of an insulating mineral. Radiation emitted from radioactive isotopes ionizes atoms, and electrons are transferred from the ground state (valence band) to the conduction band. After a short time of diffusion most electrons recombine with holes that are located near the valence band. Some electrons are trapped at charge deficit sites (defects), forming paramagnetic centers that can be detected with electron spin resonance (ESR). The number of trapped electrons is dependent on the number of traps, the strength of the radiation field (dose rate), and the duration of radiation (=age), $E_a$ is the activation energy of the trap.

[Grün et al., 1999]
Electron Spin Resonance

![ESR Spectrum](image)

**Figure 10.** ESR spectrum at 77 K. The spectrum is dominated by the $[\text{AlO}_4]^0$ and $[\text{TiO}_4/\text{Li}^+]^0$ centers. In quartz both centers have three $g$ values. The Al center shows six hyperfine lines because of interaction with the nucleus of $^{27}$Al ($I=5/2$). Hyperfine splitting ($I=3/2$) of the Ti center is only observed for $g_y$; hyperfine splitting of $g_z$ and $g_x$ is not resolved. The starred signals may be due to the components of $[\text{TiO}_4/\text{H}^+]^0$. [Rinneberg and Weil, 1972].

[Grün et al., 1999]
**Electron Spin Resonance**

![Graph showing apparent age versus temperature for different cooling rates and trap parameters.](image)

**Figure 3.** Calculation of the apparent age for a variety of cooling rates and trap parameters of $E_a = 1.5 \text{ eV}$ and $v_0 = 2.6 \times 10^{11} \text{ s}^{-1}$. The diagram shows that if trap parameters are known, the cooling rate can be directly determined by measuring the average present-day storage temperature and apparent ESR age. The closure temperature (CT) can be obtained by extrapolating the linear part of the curve to the x axis.

[Grün et al., 1999]
Figure 2. (a) Additive dose method. The natural sample is irradiated with increasing doses and the extrapolation to zero yields $D_E$. (b) Regeneration method. The sample is reset to zero and irradiated. The projection of the natural ESR intensity onto the dose response curve yields the $D_E$ value.
Figure 11. (a) Dose response of the Al center of sample 1380. When using the additive dose method, the scatter of the data points will cause a very large uncertainty of the $D_e$ value, whereas the regeneration method produces much smaller errors. Note that each data point results from six measurements. The error bars of these repeated measurements are all within the size of the symbols. (b) Dose response of the Al center of sample 1379. The additive and regenerated dose response curves show no apparent change in sensitivity.
Electron Spin Resonance

Figure 14. Normalized natural intensities of the Al and Ti centers in both cores. The intensities of the lower core are much lower than in the upper core and decay faster. This indicates higher temperatures and a higher geothermal gradient in the lower core. Note that sample 1374 at 637 in the upper core indicates a higher temperature event.

[Grün et al., 1999]
Electron Spin Resonance

Fig. 6. Arrhenius plots of the decay factors of $E'$, Al, and Ti centers and of oxygen vacancies in quartz.

[Toyoda and Ikeya, 1991]
### Table 4. Estimated Closure Temperatures (CT) for the Al and Ti Centers

<table>
<thead>
<tr>
<th>Cooling Rate, °C Myr⁻¹</th>
<th>CT-Al, °C</th>
<th>CT-Ti, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>49</td>
<td>55</td>
</tr>
<tr>
<td>80</td>
<td>52</td>
<td>60</td>
</tr>
<tr>
<td>200</td>
<td>56</td>
<td>67</td>
</tr>
<tr>
<td>400</td>
<td>60</td>
<td>74</td>
</tr>
<tr>
<td>1000</td>
<td>64</td>
<td>82</td>
</tr>
</tbody>
</table>

### Table 2. Closure temperatures of quartz calculated by eq. (7) for two cases of cooling

**CASE 1:** The reciprocal of absolute temperature is linear as indicated by Dodson (1973).

<table>
<thead>
<tr>
<th>( b^* ) (°/deg Myr)</th>
<th>Cooling Rate (deg/Myr)</th>
<th>Closure temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^{-4} )</td>
<td>( ~ 10 )</td>
<td>91</td>
</tr>
<tr>
<td>( 10^{-3} )</td>
<td>( ~ 100 )</td>
<td>123</td>
</tr>
<tr>
<td>( 10^{-2} )</td>
<td>( ~ 1000 )</td>
<td>162</td>
</tr>
</tbody>
</table>

[Grün et al., 1999]

[Toyoda and Ikeya, 1991]
Cosmogenic
The most important cosmogenic nuclides

<table>
<thead>
<tr>
<th>nuclide</th>
<th>half-life</th>
<th>target elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$He</td>
<td>stable</td>
<td>O, Si, Al, Mg</td>
</tr>
<tr>
<td>$^{10}$Be</td>
<td>1.4 Myr</td>
<td>O, Si, Al</td>
</tr>
<tr>
<td>$^{21}$Ne</td>
<td>stable</td>
<td>Mg, Na, Si, Al</td>
</tr>
<tr>
<td>$^{26}$Al</td>
<td>0.7 Myr</td>
<td>Si, Al</td>
</tr>
<tr>
<td>$^{36}$Cl</td>
<td>0.3 Myr</td>
<td>Cl, K, Ca</td>
</tr>
</tbody>
</table>

Minerals: quartz, olivine, pyroxene

[Hetzel, 2009]
Cosmogenic dating

Figure 4. Cosmogenic reactions for $^{36}$Cl. Fast and thermal neutrons and slow muons interact with three main target elements, $^{35}$Cl, $^{39}$K and $^{40}$Ca, to produce $^{36}$Cl with probabilities $P$. Formation of $^{36}$Cl is accompanied by the emission of various elementary particles.

[Zreda and Phillips, 2000]
Dating techniques for the Quaternary

1. Cosmogenic nuclides
2. $^{14}$C-dating
3. Luminescence dating
4. Fission track and (U-Th)/He dating
5. U-Th disequilibrium methods ...

[Hetzel, 2009]
1. Cosmogenic nuclides

Applications of cosmogenic nuclides

DATES:
- fluvial & marine terraces, pediments, moraines, landslides, lava flows, strandlines of lakes

RATES:
- Slip rates of active faults
- Rates of erosion (or denudation)
  - a) local (at a single point)
  - b) averaged (over river catchments)

Reconstructions:
- Extent and stability of continental ice shields
- Retreat of glaciers since last glacial maximum

[Hetzel, 2009]
Cosmogenic dating

Fig. 1. Depth dependence of $^{26}$Al and $^{10}$Be production rates. Left panel, contribution of spallation ($P_{sp}$), negative muon capture ($P_{\mu-}$), and fast muon interactions ($P_{fast}$) to $^{10}$Be production in quartz. Surface production rate of $^{10}$Be by spallation assumed to be 7 atoms g$^{-1}$ yr$^{-1}$. $P_{fast}$ and $P_{\mu-}$ are calculated using muon interaction cross-sections inferred from measurements at Wyangla Quarry, Australia, as described in text (J. Stone, unpublished data). Right panel, effect of uncertainty in muon interaction cross-sections on total production rates of $^{10}$Be and $^{26}$Al. Solid lines, Wyangla Quarry cross-sections; dashed lines, cross-sections from Heisinger (2002a, 2002b).

[Balco et al., 2005]
Cosmogenic dating
Cosmogenic dating

Figure 7. Incident cosmic ray intensity at a fault face inclined at an angle $\beta$. The cosmic-ray intensity depends on the direction according to Equation 6; the highest intensity is in the vertical direction (longest line), whereas the horizontal contribution is zero. Fault face is exposed to cosmic rays over the angle $180-\beta$ (solid lines) and shielded from cosmic rays over the remaining angle $\beta$ (dashed lines).

[Zreda and Phillips, 2000]
Cosmogenic dating

Figure 3. (A) Reconstructed geomagnetic field intensity in the last 85 ky (from Mazaud and others, 1991). (B) Integrated geomagnetic field intensity for the same time interval. The graph shows the value of average intensity between a given point in time and the present.

[Zreda and Phillips, 2000]
Cosmogenic dating

Table 2.2: Production rates $P_0$ of cosmogenic nuclides in quartz at sea level and latitudes = 60°.

<table>
<thead>
<tr>
<th>Cosmogenic nuclide</th>
<th>$P(^{10}\text{Be})$ [atoms/yr·g SiO$_2$]</th>
<th>$P(^{26}\text{Al})$ [atoms/yr·g SiO$_2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nishiizumi et al. (1989)</td>
<td>6.03 ± 0.29</td>
<td>36.8 ± 2.7</td>
</tr>
<tr>
<td>Lal (1991), (based on Nishiizumi et al., 1989)</td>
<td>5.994</td>
<td>36.67</td>
</tr>
<tr>
<td>Nishiizumi et al. (1996)</td>
<td>5.80</td>
<td>(35.4)*</td>
</tr>
<tr>
<td>Kubik et al. (1998)</td>
<td>5.75 ± 0.24</td>
<td>37.4 ± 1.9</td>
</tr>
</tbody>
</table>

The concentration of the radioactive cosmogenic nuclides $^{10}\text{Be}$ and $^{26}\text{Al}$ produced in the Earth’s surface is described with equation Eq. 2.1, where $N$ is the number of cosmogenic nuclides per gram quartz, $P$ is the production rate function in units of atoms per year and gram quartz and $\lambda$ is the particular decay constant in units of per year. Note that the concentration of $N$, the production rate $P$ and also the spatial variable $x$ are time-dependent.

$$\text{Eq. 2.1} \quad \frac{dN(x(t),t)}{dt} = -N(x(t),t)\lambda + P(x(t),t)$$

[Tschudi, 2000]
Cosmogenic dating
Cosmogenic dating

Fig. 2.2: Altitude-weight graph, where the amount of quartz needed is shown for a sample at latitude 40°N and within an altitude range of 0 to 4’000 m asl. The amount of quartz is calculated for assumed exposure ages between 5 and 11 ky. The calculations are based on production rates of Kubik et al. (1998) and the scaling formalism of Lal (1991) with a $^9$Be carrier addition of 0.3 mg.

[Tschudi, 2000]
Cosmogenic dating

Figure 5. Accumulation of radioactive and stable cosmogenic nuclides in rocks exposed continuously at the surface. Radioactive nuclides reach a limit determined by the production and decay rates. The production rates are assumed constant with time.

[Zreda and Phillips, 2000]
Concentration of cosmogenic nuclides as function of exposure time (NO EROSION)

$^3\text{He} = \text{stable}$

$^{21}\text{Ne} = \text{stable}$

$^{26}\text{Al}: T_{1/2} = 0.7 \text{ Myr}$

$^{10}\text{Be}: T_{1/2} = 1.5 \text{ Myr}$

[Hetzel, 2009]
Cosmogenic dating

Production rate:
1 atom/g/year
(no erosion)
Cosmogenic dating
estimation of erosion rate

![Graph showing cosmogenic dating and erosion rate estimation](image_url)
Cosmogenic dating

Figure 2. Measured $^{10}$Be concentrations for Santa Cruz terraces T1–T5. Reported depths are averages of each ~10 cm sampling interval.

[Perg et al., 2001]
Cosmogenic dating

Figure 4. Numerical model of $^{10}\text{Be}$ profile evolution, shown at 25 k.y. intervals (gray lines), with measured cosmogenic radionuclide (CRN) profiles (black diamonds). Model includes uniform inheritance, steady CRN production, and bioturbation, assumed to homogenize CRN concentrations over fixed depth. Inheritance is set using mean inheritance calculated from equation 5 (Table 1; gray line labeled 0 ka). $P_{0,SLHL} = 5.55 \text{ atoms g}^{-1}\text{yr}^{-1}$; $z^* = 84–100 \text{ cm}$, depending on average density of soil profile (see text). Bold black line indicates analytic model ages (equation 4; Table 1).

[Perg et al., 2001]
Cosmogenic dating

Figure 3. Uplift model using terrace ages corresponding to marine isotope stages (MIS) 3, 5a, 5c, 5e, and 7. Left: Terrace inner edge elevations near sample sites (Anderson and Menking, 1994) and approximate local terrace widths. Right: Sea-level history since 225 ka from Papua New Guinea (Chappel and Shackleton, 1986), augmented (black circles) with MIS 5 sea-level elevations for California (Muhs et al., 1994). Dark gray lines: cosmogenic radionuclide ages with light gray error boxes of ±10 k.y. Slope of lines connecting present inner edge elevation with appropriate sea-level highstand elevation give uplift rates, indicating steady uplift of 1.1 mm/yr over past 250 k.y.

[Perg et al., 2001]
Cosmogenic dating

[Figure: Graph showing the relationship between \(^{10}\text{Be}\) concentration (\(10^5\) atoms g\(^{-1}\)) and percent of sample with grain size >2 mm. The graph indicates a relationship where higher concentrations correspond to higher percentages of large grains. A shaded area labeled "landslide material" suggests a threshold or characteristic for landslide material.]

[Riebe et al., 2003]
Cosmogenic dating and analysis of scarps along the Solitario Canyon and Windy Wash Faults, Yucca Mountain, Nevada

Figure 2. View looking east at western slope of Yucca Mountain (total relief 300 m), showing bedrock scarp along a strand of Solitario Canyon fault. Arrows bound segment of scarp that was studied.
Figure 8. Fault scarp profiles in the central and eastern part of the Zhangye thrust. Profiles have no vertical exaggeration. For location see Figure 3a.
Cosmogenic dating of fault scarps

[Hetzel et al., 2004]
Cosmogenic dating

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Mechanism</th>
<th>Rate</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{21}\text{Ne}$</td>
<td>Spallation</td>
<td>45 atoms (g olivine)$^{-1}$ y$^{-1}$</td>
<td>17,800 calendar yr</td>
</tr>
<tr>
<td>$^{3}\text{He}$</td>
<td>Spallation</td>
<td>115 atoms (g olivine)$^{-1}$ y$^{-1}$</td>
<td>2,200-14,500 $^{14}\text{C}$ yr</td>
</tr>
<tr>
<td>$^{10}\text{Be}$</td>
<td>Spallation, Muon capture</td>
<td>5 atoms (g SiO$_2$)$^{-1}$ y$^{-1}$</td>
<td>ca. 11,000 calendar yr (estimated)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 atom (g SiO$_2$)$^{-1}$ y$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$^{14}\text{C}$</td>
<td>Spallation</td>
<td>20 atoms (g basalt)$^{-1}$ y$^{-1}$</td>
<td>17,800 calendar yr</td>
</tr>
<tr>
<td>$^{26}\text{Al}$</td>
<td>Spallation, Muon capture</td>
<td>30 atoms (g SiO$_2$)$^{-1}$ y$^{-1}$</td>
<td>ca. 11,000 calendar yr (estimated)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 atoms (g SiO$_2$)$^{-1}$ y$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$^{36}\text{Cl}$</td>
<td>Spallation of $^{39}\text{K}$, Spallation of $^{40}\text{Ca}$, Activation of $^{35}\text{Cl}$</td>
<td>7,520 atoms (mol K)$^{-1}$ y$^{-1}$</td>
<td>2,200-55,000 calendar yr</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2,900 atoms (mol Ca)$^{-1}$ y$^{-1}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>313,500 n (kg rock)$^{-1}$ y$^{-1}$</td>
<td></td>
</tr>
</tbody>
</table>

[Zreda and Phillips, 2000]
Cosmogenic dating

Fig. 2.3: Many parameters affect the method of SED. Shielding, vegetation, snow and tectonic uplift influence the local incoming cosmic ray flux and therefore the local production rate. Earth surface dynamics, vegetation, erosion and other unknown processes may disintegrate the target rock and change its original orientation. Example: Erratic boulder, Kola Peninsula, Russia.