1) 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

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

3) Volcanic events (= formation ages)

   Basement exhumation (= cooling ages)

4) Complex T histories of basins & thermal modelling
5) Detrital geochronology (provenance by single-grain ages)
6) (U-Th)/He thermochronology
7) K/Ar, Ar/Ar, Luminescence, ESR and cosmogenic dating of sediments
8) U/Pb and U/Th dating of sediments
Fission tracks in an apatite crystal

(polished and etched by nitric acid – locality: Bohemian Massif)
The principal types of thermal histories

- Track stability zone
- Partial annealing zone (PAZ)
- Track instability

Temperature vs. Time diagram:
- FORMATION AGE
- COOLING AGE
- MIXED AGE

[Wagner, 1979]
Good correlation between FT and independent ages (in case of samples with simple thermal history)
Precise dating in the "gray range", between the main fields of C-14 and K/Ar
Dating of volcanic ash layers in the key sections of hominoid evolution

\[ \text{Zircon FT age: 1.87 \pm 0.04 Ma} \]  

\[ \text{KNM-ER 3733 } \]
\[ \text{Homo erectus} \]

\[ \text{KNM-ER 406 } \]
\[ \text{Australopithecus boisei} \]

\[ \text{KNM-ER 1470 } \]
\[ \text{Homo} \]

\[ \text{Without tuff} \]

[Gledow, 1980]
Dating of fire-reset objects in archaeology

- zircons in pottery
- burned obsidian arrowhead
- detrital titanite in the sand
Tracks in glass inclusions of quartz phenocrysts of a weathered pumice

[Vincent et al., 1984]
Dating of infiltration and deposition of U-ore in the pore space of a sandstone (Q grains as natural external detectors)

Host rock: Jurassic sandstone, FT age: 6.7 ± 0.7 Ma
The principal types of thermal histories

[Diagram showing thermal histories with labels for track stability zone, partial annealing zone (PAZ), track instability, formation age, cooling age, and mixed age. Temperatures indicated at ~60 °C and ~120 °C. Diagram based on Wagner, 1979.]
The principle of closure temperature

Closure Temperature Definition
after Dodson (1973)

Temp.

$T_c$

D/P

$0$

AGE
Summary of "closure temperatures"

- Igneous processes/ high-grade metamorphism
  - Zircon U/Pb
  - Monazite U/Pb
  - Titanite U/Pb
  - Hornblende Ar/Ar
- Metamorphism/ mid-crustal processes
  - Muscovite Ar/Ar
  - Biotite Ar/Ar
  - K-feldspar Ar/Ar
  - Titanite fission track
  - Zircon fission track
- Sedimentary basins/ burial metamorphism
  - Titanite (U-Th)/He
  - Zircon (U-Th)/He
  - Apatite fission track
- Topography/ surface processes
  - Apatite (U-Th)/He

but how?

[Anna K. Ksienzyk]
Post-emplacement rapid cooling
Annealing of fission tracks in laboratory heating experiments

[Images of Durango induced fission tracks at 310°C, 352°C, and 366°C for 1 hour, with [from Kounov] citation]
Arrhenius plot of annealing results of a “Lybian Desert Glass” sample

[Wagner, 1979]
Laboratory and natural annealing

[Diagram showing relationships between time and temperature for different track loss percentages.]

[Experimental results: ○ 0 - 50% track loss, ● 50 - 100% track loss.]

[Source: Gleadow and Duddy, 1981]
Reset of apatite and sphene FT ages in a granite batholite from the contact of a basalt dike

[Calk & Naeser, 1973]
Track annealing and organic maturation

[Naeser et al., 1989]
Isothermal retention curves (at 10 and 90 % retentions)

[Reiners and Brandon, 2006]
Dependence of “closure temperatures” on cooling rate

Figure 14.6. Apparent closure (annealing) temperatures of fission tracks as a function of cooling rate for a variety of minerals.
Published closure temperature values for zircon

<table>
<thead>
<tr>
<th></th>
<th>Temperature</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lal et al. (1980)</td>
<td>380 ± 50</td>
<td>lab. annealing</td>
</tr>
<tr>
<td>Bal et al. (1983)</td>
<td>300</td>
<td>lab. annealing</td>
</tr>
<tr>
<td>Gleadow and Brooks (1979)</td>
<td>200 ± 50</td>
<td>cooling path (Himalaya)</td>
</tr>
<tr>
<td>Lewis (1990)</td>
<td>234 ± 10</td>
<td>cooling, geology</td>
</tr>
<tr>
<td>Carter (1990)</td>
<td>200 ~</td>
<td>cooling path</td>
</tr>
<tr>
<td>Zeitler et al. (1982)</td>
<td>190-210</td>
<td>slow-fast (Himalaya)</td>
</tr>
<tr>
<td>Michalski-Soom (1990)</td>
<td>200-250</td>
<td>cooling path</td>
</tr>
<tr>
<td>Hasebe et al. (1993)</td>
<td>Z-PAZ: 190-260</td>
<td></td>
</tr>
<tr>
<td>Koul et al. (1988)</td>
<td>172</td>
<td>cooling path</td>
</tr>
<tr>
<td><strong>Hurford (1986)</strong></td>
<td><strong>240 ± 50</strong></td>
<td>cooling path (Alps)</td>
</tr>
<tr>
<td><strong>Harrison et al. (1978)</strong></td>
<td><strong>175 ± 25</strong></td>
<td>cooling path</td>
</tr>
<tr>
<td>Zau and Wagner (1985)</td>
<td>195 ± 20</td>
<td>0.1 °C/Ma (Urach III)</td>
</tr>
<tr>
<td></td>
<td>210</td>
<td>1 °C/Ma</td>
</tr>
<tr>
<td></td>
<td>225</td>
<td>10 °C/Ma</td>
</tr>
<tr>
<td>Koshimizu (1990)</td>
<td>210</td>
<td>internal surf.</td>
</tr>
<tr>
<td></td>
<td>390</td>
<td>external surf.</td>
</tr>
<tr>
<td>Duane and Brown (1991)</td>
<td>intergrain differences (chemistry, alpha-tr.)</td>
<td></td>
</tr>
</tbody>
</table>
Empirical zircon FT reset time/temperature range

Fig. 4 Constraints on the zircon FT PAZ (modified after Rahn et al., 2004). Light grey: range of the PAZ constrained by fanning annealing models. Dark grey: PAZ derived from geologic evidence. Highest temperatures for the upper (high-temperature) boundary of the PAZ are calculated on the basis of annealing experiments with α damage-free zircon samples (Rahn et al., 2004). Lowest temperatures are derived from geologic examples with long-duration heating episodes (e.g., Zaun and Wagner, 1985).

[Timar-Geng et al., 2004]
Dependence of apatite FT reset on the amount of chlorine secondary anion

[Green et al., 1985]
Diameter of the etched tracks:
Dpar - a measure of the track stability and the state of the crystal lattice
Different apatites chemistry give different Dpar values and closure temperatures.
Multimethod thermochronology

Elevation profile (1 method)

Exhuming mountains  Vertical age distribution

rising relief
samples
shifting isotherms

Apatite fission track age

Temperature [°C]

hornblende K/Ar
biotite Rb/Sr
biotite K/Ar
zircon FT
cooling path
apatite FT

Time

Elevation [meter a.s.l.]

old
young

now

1000
2000
500
300
100

1000

2000

Multimethod thermochronology

1000
2000

2000

1000

2000

1000

2000
Multi method thermochronology

(e.g. AFT and ZFT on one sample)

Using only one method

- FT ages from a vertical profile
- FT ages from a horizontal profile
- areal distribution of ages
Vertical distribution of apatite and zircon FT ages in a steady state crust
Generation of vertical age gradient

Closure temperature:
Apatite FT 110 °C

Exhumation

[Anna K. Ksienzyk]
Vertical distribution of apatite FT ages in a steady state and continuously exhuming crust
This is the first age / elevation profile

[Wagner et al., 1977]
Figure 14.7. Apatite fission track ages vs. altitude for metamorphic rocks of the Higher Himalaya Crystalline belt of Kashmir. The correlation coefficient is 0.88. The slope indicates an uplift rate of 350 m/Ma. From Kumar et al. (1995).
Age / elevation profile vs. cooling rate

\[
\frac{dz}{dt} = \frac{dT}{dt} = \frac{6.8 \ ^\circ \text{C}/\text{Ma}}{0.030 \ ^\circ \text{C}/\text{m}} = 226 \ \text{m/Ma}
\]

\[
\frac{dT}{dt} = \frac{95 - 10}{12.5} = 6.8 ^\circ \text{C}/\text{Ma}
\]
Vertical distribution of apatite FT ages in a steady state crust and after an erosional event

[Naeser, 1979]
PAZ (= partial annealing zone)

[Grist and Zentilli, 2006]
Bad Urach geothermal history

Vertical fission track age trend at Bad Urach Geothermal anomaly

[Hammerschmidt et al., 1984]
Verticalapatite FT age distribution in the KTB borehole

Fig. 3 Apatite fission-track age and mean track length plotted against present sample depth. The measured data are indicated by the open circles with 1 SD error bars. The thick gray dashed line indicates the fission-track results predicted by the thermal model shown in Fig. 2. The modelled profile reproduces the observed data remarkably well from for depths between 4000 and 1500 m. However, for depths shallower than 1500 m the model systematically overpredicts both the fission-track age and mean track length. If part of the modelled VB section, between ~1500 and 1000 m, is simply repeated to make up the upper 1500 m of the profile, a substantially better fit is obtained between the observed and predicted results. This is shown by the three black dashed lines.
Typical "break in slope" with track length distributions (Antarctica)

[Image of a graph showing track length distributions across different elevations, with data points and mean values indicated.]

[Fitzgerald, 1992]
Fig. 4  Three possible models explain the significant change in mean track length along the borehole: (a) thermal anomaly along the fault; (b) local uplift of the fossil zircon partial annealing zone (PAZ) by the reverse component of the fault motion; and (c) regional uplift of the fossil PAZ. Considering the geophysical and geological constraints of the studied area, the present zircon track length data are best explained by model a.
Apatite fission track age as a function of distance from the present-day coast at rifted continental margins

[Gallagher et al., 1998]
Cartoons of different models for the evolution of passive margin models and the predicted spatial trend in apatite fission track data.

[Gallagher et al., 1998]
Eroded rift shoulder and sediment fill

Results of backstripping/backstacking for the Saudi Arabian Red Sea margin and the Transantarctic Mountains–Victoria Land Basin for different models of lithospheric strength. Lower parts show sediment fill of the basin determined from seismic data (from [45] for the Red Sea and [48] for the Ross Sea) and estimated amount of erosion on the flanks. Mesozoic sediments in the Ross Sea basin were not backstripped, in contrast to the continental ice sheet. Upper parts show reconstructed tectonic uplift/subsidence patterns for different isostatic compensation models. For the Saudi Arabian Red Sea margin, a model with erosion up to 200 km inland is also shown (thin line).

[van der Beek et al., 1994]
Jump in thermal histories in profiles across faults

[Steenken et al., 2002]
Colorado Plateau – Basin and Range bedrock apatite fission-track ages
Exhumation rate from thermochronologic data (Gold Butte block in SE Nevada)

Hanging wall block moved to southwest during Miocene extension

[Present situation]

[Pre-exhumational reconstruction]

[Wernicke and Axen, 1988]
FT ages along low-angle normal faults

Fitzgerald et al. (1993)

The authors are not sure in that Sierra Esterella is a footwall unit. If it is then the apatite ages yield a slip rate (or rate of extension) of ~0.3 cm/yr.

Other metamorphic core complexes:
- Whipple fault 0.7 cm/yr (Davis and Lister, 1988)
- Chemehuevi 0.2-0.5 cm/yr (Foster et al., 1990)
- Harcuvar 0.7 cm/yr (Foster et al., 1993)
Profile sampling along a tunnel
What can we found in a mountain?

[Foeken et al., 2007]
Mean elevation of topography through the Cascades at about Seattle, with apatite (U-Th)/He ages

[Reiners and Brandon, 2006]
Dependence of erosion and precipitation

[Reiners and Brandon, 2006]
Tele-thermal effect of a hidden intrusion

[Naeser, 1989]

[Kelly and Wagner, 1977]
Contoured apatite FT ages ---- isolines are crossing big faults WOW!
let’s go to cinema

(Namibia thermo movie)

[Raab, 2001]