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

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
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 are indicated at ~60 °C and ~120 °C.]

[Wagner, 1979]
Track shortening

Schematic diagram illustrating the stages of thermal annealing of fission tracks as reconstructed from chemical etching studies and TEM observations. (a) Pre-annealed track length and morphology. (b) Initial shortening of the track length (Green et al., 1986). (c) Development of an irregular (non-linear) morphology at the track–matrix boundary. (d) Segmentation of the track length. (e) Segment spacing is maximized and the segment shape approaches a sphere. (f) Instantaneous healing of spheres (not observed in this study).

[Paul, 1993]
Confined horizontal tracks are developing below the surface along tracks and clevages

[Crowley, 1989]
Measurement of track length  (on horizontal confined fission tracks)

transmitted light

reflected light

[GÖochronology]
Relation of thermal history and track length distribution

[after Sanders, 1998]
Boomerang plots

[Green, 1986]
Boomerang plots

[Boomerang plots from different regions: SE Australia, SE Brazil, SW Africa, Yemen, W. India, with ages ranging from 0 to 500 Ma]

[Gallagher et al., 1998]
$\text{Cf}^{252}$ irradiation to increase the number of the observable horizontal confined tracks:

- Cf-source
- Fission fragments

(vacuum)

- Apatite crystals
- (latent) Spontaneous tracks
- (latent) Fission tracks of the outer source

After etching
"Drilling" the surface by accelerated heavy ions
Track shortening on an Arrhenius diagram

**Arrhenius, Svante August**
Figure 14.8. Hypothetical time-temperature paths and the distribution of track lengths that should result from these paths. From Ravenhurst and Donelick (1992).

[Gallagher et al., 1998]
Fission track dating: track length distribution → cooling history

[Anna K. Ksienzyk]
Modelling – major decisions

Forward – inverse modelling

Supervised - unsupervised

Input data
Initial conditions
Selection of model (algorithm, parameters)
Modelling (black box)
Test of results
Principle of the computation of track length distribution
HeFTy demo

model1.hft
MonteTrax – there are no strict time constraints
Case 1
AFT age = 72.1 Ma
mean = 14.59 microns
σ = 2.57 microns

Case 2
AFT age = 60.3 Ma
mean = 11.45 microns
σ = 1.03 microns

a) Case 1: Accepted thermal histories
b) Case 1: Probability density

a) Case 2: Accepted thermal histories
b) Case 2: Probability density

[Corrigan, 1991]
Result of an “unsupervised” thermal modeling

Malé Karpaty

Known rifting event (elevated heat flow)

[Danisik et al., in press]
Thermal modeling must be preluded by a review of geological events and their thermal consequences.

These dates can be the turning points of the thermal history and thus the time-temperature constraints of the modeling.

[Glasmacher et al. 2002]
$tT_1$ = age and temperature of metamorphism

$T_{max}$ = maximum temperature during burial

$T_{max}$ = maximum temperature during burial

$tT_1$ = age and temperature of metamorphism

$tT_2$ = 0 Ma; recent annual mean temperature

$tT_3$ = 0 Ma; recent annual mean temperature

$T_{max}$ = maximum temperature during burial

$T_{max}$ = maximum temperature during burial

$tT_1$ = age and temperature of metamorphism

$tT_2$ = age of sedimentation; annual mean temperature

$tT_3$ = 0 Ma; recent annual mean temperature

$tT_1$ = age and temperature of metamorphism

$tT_2$ = age of sedimentation; annual mean temperature

$tT_3$ = 0 Ma; recent annual mean temperature

Metamorphites exposed (fix points)

- Exhumation
- Burial

Temperature [°C]

Million Years

- A
- B
- C
Thermal history of accreting sediments

Thermal history of the Tei melange, Hwana unit, and Naharigawa unit, which are representative examples of Cretaceous melange, Cretaceous turbidite, and Eocene turbidite, respectively. Open circles show the depositional ages with possible depositional duration. Solid circles show time-temperature points estimated from FT ages. Solid squares show the maximum possible temperature derived from FT zircon data, and their timing based on K-Ar cleavage ages (Agar and others, 1989).

Schematic diagram representing the tectonic history of the offscraped and underplated materials under the framework of constant wedge shape and 20°C/km thermal gradient [Hasebe et al., 1993a]. 50-160 °C/km also reported [Hasebe et al., 1993b].
Geological constraints for thermal modelling of the evolution of the Carpathian flysch belt

[Botor et al. in prep.]
Results of modelling the thermal histories of the major Carpathian nappes (AFTSolve, Ketcham, 2000). Dominant and common is an extremely rapid warming up period.
Simplified model of thermal history of the Silesian Unit

Thermal history of Silesian nappe

- Major periods
  - sedimentary burial
  - tectonic burial
  - exhumation by folding and erosion
  - sedimentation of volcanic tuff
  - termination of sedimentation by thrusting
  - detachment and accretion

![Graph showing temperature vs. age with major periods labeled](image)
Accretional evolution of the Southern Western Carpathians

- 27 Ma
- Western Carpathians
- European plate

- 24 Ma

- 25 Ma

- 22 Ma

- Magura
- Silesian
- active major thrust
- isotherm of Cl-apatite FT reset
Normal faults are also common in the Carpathian thrust pile

[Oszczypko-Clowes and Oszczypko 2004]
Geothermal gradient: **20 (18-25) °C/km**
Closure temperature: **145 (135-150) °C**
Angle of subduction: **23 (22-25) °**
Time lag between overthrust and reset: **2 (1.5-2.5) Ma**
Horizontal speed of subduction: **~8.8 (5.5-9.5) km/Ma**

\[ V = \left( \frac{T_{\text{closure}}}{g g} \right) \times \cotg(\alpha) \times \text{Time}_{O-R} \]
Thermal histories of two, neighbouring metamorphite bodies

- Deposition of Mesozoic sediments on Wechsel unit
- Thrusting
- Eocene sedimentation
- Miocene extension and sedimentation
- Deposition of Mesozoic sediments on Wechsel unit

Thermal histories of two, neighbouring metamorphite bodies:
- Apatite PAZ
- Zircon PAZ
- Wh. mica K/Ar

- Wechsel unit
- Grobgneis unit at the northern margin of the Wechsel Window
Thermochronology -> exhumation -> ?relief?

- Cretaceous
- Paleocene
- Eocene
- Oligocene
- Miocene
- Pliocene

Major events:
- Cooling after Eoalpine metamorphism
- Gosau sed.
- Post-Gosau compression
- Reef, red clay, peneplain
- Major subsidence in intramontane basins
- Periadriatic magmatism

Main trends in exhumation & subsidence:
- Exh.
- Subs.

Relief:
- Mountainous
- Hills-lowlands
- Sedimentation

Austroalpine crystalline
- Austroalpine crystalline (in the north, where Cretaceous apatite FT ages preserved)
- Austroalpine crystalline (in the south, where Oligocene apatite FT ages are common)
- Austroalpine Paleozoic metasediments and post-Variscan cover

[Dunkl et al., unpublished]
Reset of apatite FT ages during burial
Confrontation of burial history and apatite FT reset

“the Puszta in winter-time”
65-85 Ma: typical Eoalpine cooling ages and unreset ages in the sediments

Trend in reset

Elevated isotherms
Reset of the FT thermochronometer

Exhumation

Change in heat-flow

- Permian (~250 Ma),
- Late Triassic (~220 Ma),
- Jurassic (180 - 140 Ma),
- Oligocene (~30 Ma),
- Pliocene-Quat. (4-2 Ma)

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- Late Cretaceous (~80 Ma),
- Miocene (18 - 10 Ma)

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zero zircon FT age

PAZ

mica Ar reset
Thermochronologic assessment of a hydrocarbon play

[Diagram showing temperature intervals and corresponding stability of fission tracks in apatite and vitrinite reflectance Ro.]

- Temperature [°C]: 200, 150, 100, 50
- Fission tracks in apatite: unstable, partially stable, stable
- Vitrinite reflectance Ro [%]: 1.3, 0.8, 0.5

- Duration of heating [Ma]: 100, 30, 10, 5, 3

- Mesozoic thermal event
- Neogene-Quaternary thermal event

[isolines after Gleadow et al., 1983]
Joint modelling of thermochronology and organic maturation

- **Eastern Alps**
  - WSW: Schöckl
  - ENE: Rechnitz Window

- **Pannonian basin**
  - Danube basin
  - 200 km

**Vertical movement since Middle Miocene:**
- **Uplift**
- **Subsidence**

**Legend:**
- Post-rift sediments
- Syn-rift sediments
- Early-Middle Miocene normal faults
- Austroalpine Paleozoic
- Austroalpine basement
- Penninic
- Hanging wall and sediment remnants on top of the Penninic window (sample sites)

**Sample site:**
- WSW
- ENE
- Modeled heat flow of this section is in Figure 10

**Maps and Figures:**
- Eastern Alps
- Pannonian basin
- Carpathians
- Dinarids
- Rechnitz Window
- Penninic windows
Modelling of vitrinite reflectance

Variables:
- heat flux
- burial

Output:
- coal rank

Known erosional periods: "Styrian", "Sarmatian-Pannonian", "Pliocene"
Reconstruction of paleo-burial

Range of the heat flow in the hangingwall

Heat flow [mW/m²]

Range of the necessary burial for the observed vitrinite reflectance

Burial thickness [m]

Vitrinite reflectance (%) = 0.8

Coal rank of the Sinnersdorf beds

[Dunkl et al., 1998]
Basin inversion: estimation of the removed section

[Images of graphs and data plots showing the relationship between geothermal gradient and removed section, with annotations for data from Hans-1 and Tønder-2,-3 wells.]

[Japsen et al., 2007]
Reconstructed burial-exhumation history
(note the Late-Paleogene surface temperature drop)

[Japsen et al., 2007]
Reconstruction of the inverted part of the North Sea

[Japsen et al., 2007]
Estimation of the eroded thickness by modelling

(b) Model results, well BKZ-01

(B1) Burial and thermal history

(B2) Vitrinite

Reflectance

GOF=0.49

Depth (km)

Heat flow

(mW/m²)

Time (Ma)

0.0
0.5
1.0
1.5
2.0

0.0
0.5
1.0
1.5
2.0

0.0
0.5
1.0
1.5
2.0

0.0
0.5
1.0
1.5
2.0

Response of simulated vitrinite reflectance and fission track age and length data to Late Cretaceous exhumation of (a) 250 and (b) 1000 m.

GOF denotes value of the fit statistic; a value of 1 is a perfect fit of the simulated and the observed data.

[Luijendijk et al., 2011]
Estimation of the eroded thickness by modelling

Model fit statistics of all Late Cretaceous exhumation and basal heat flow model scenarios.

[Luijendijk et al., 2011]