Introduction to Quantitative Geology
Laboratory exercises 6-7
Quantitative thermochronology

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The Himalaya of Bhutan
Thermochronometer ages in western Bhutan

Respectively, these structures separate the very low-grade metamorphic Tethyan Sedimentary Sequence (TSS), the amphibolite to granulite/eclogite facies rocks of the Greater Himalayan Sequence (GHS), the green schist facies rocks of the Lesser Himalaya Sequence (LHS), and the Mio-Pliocene synorogenic sub-Himalaya foreland sediments, which are thrust over the modern Ganges-Brahmaputra foreland basin along the active MFT. Aspects of the geology and geomorphology in the Bhutan Himalaya, however, suggest a unique tectonic history likely owing to its pre-Neogene tectonometamorphic and exhumation history [Grujic et al., 1996, 2002, 2006; Hollister and Grujic, 2006; Kellett et al., 2009; Swapp and Hollister, 1991; Warren et al., 2011b]. In the sections below, we summarize the results of previous geological and geophysical studies that will serve as key constraints for the parameter range of the thermokinematic models. We emphasize that we are not intending to give a full account of the thermokinematic evolution of the Himalaya orogeny, but we focus on the Bhutanese part only.

2.1. Geology of Bhutan

2.1.1. The Tethyan Sedimentary Sequence (TSS) and the South Tibetan Detachment System (STDS)

The TSS in Bhutan comprises deformed sedimentary cover from the northern margin of the Indian Plate separated from the underlying high-grade metamorphic rocks of the GHS by the two structurally distinct segments of the STDS [Burchfiel and Royden, 1985; Burg and Chen, 1984; Hollister and Grujic, 2006]. The TSS is exposed between the Indus-Tsangpo suture and the trace of the STDS as well as in a string of klippen atop the GHS (Figures 1 and 2). Preserved at the base of klippen, the Outer South Tibetan Detachment shear zone (O-STD) [Kellett et al., 2009] is characterized by top-down-to-the-north shearing with a strong component of vertical shortening and was active between circa 24–22 Ma and circa 16 Ma [Chambers et al., 2011; Corrie et al., 2011].

Figure 1. Geological map of the Eastern Himalaya [after Grujic et al., 2011, and references therein]. Dark grey frame on map in inset shows location of Figure 1. Abbreviations are: MFT, Main Frontal Thrust; MBT, Main Boundary Thrust; RT, Ramgarh Thrust; MCT, Main Central Thrust; HHT, High Himalayan Thrust; KT, Kakhtang Thrust; O-STD, Outer South Tibetan Detachment; I-STD, Inner South Tibetan Detachment.
Linking ages to geological processes

- Thermochronometer ages contain valuable information about past geological processes, but age interpretation is difficult.
Estimating rock exhumation rates

- In mountainous settings, rock exhumation is the result of a erosional (surface) and/or tectonic processes

- **Exhumation**: The unroofing history of a rock, as caused by tectonic and/or surficial processes (Ring et al., 1999)

Grand Teton National Park, Wyoming, USA
Estimating exhumation rates from ages

- The simplest way to estimate a long-term average exhumation rate from a thermochronometer age is to assume a constant geothermal gradient and determine the depth from which the sample was exhumed.

- For example, assume we measure an apatite (U-Th)/He age of 12.3±0.9 Ma in a sample.

- Assume a nominal closure temperature $T_c$ of 75±5°C and a “typical” geothermal gradient of 20°C/km.

- How would you find the exhumation rate?
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- **How would you find the exhumation rate?**

  - The simple approach is to find the depth of $T_c$ and divide that depth by the age.
Exhumation rate example

- If we assume the surface temperature is 0°C, the depth $z_c$ of $T_c$ is simply $T_c$ divided by the geothermal gradient
  \[ z_c = \frac{75°C}{20°C/km} = 3.75 \text{ km} \]

- An **exhumation rate** $\dot{e}$ can be estimated by dividing that depth by the measured age
  \[ \dot{e} = \frac{3.75 \text{ km}}{12.3 \text{ Ma}} = \sim 0.3 \text{ km/Ma} = \sim 0.3 \text{ mm/a} \]
A constant thermal gradient is a bad idea

- This approach works, but it neglects many known thermal factors including ‘bending’ of the geotherm as a result of thermal advection

- A more reasonable approach would be to utilize a 1-D thermal model to simulate heat transfer processes during rock cooling, which will be our approach in the final two lab exercises
Advection is often the main thermal influence on thermochronometer ages in mountainous regions.

Thus, advection must be considered by using an appropriate equation:

\[ T(z) = T_L \left( \frac{1 - e^{-\left(\frac{v_z z}{\kappa}\right)}}{1 - e^{-\left(\frac{v_z L}{\kappa}\right)}} \right) \]
Now what?

- With a predicted 1-D thermal field, the next step is to determine the **cooling history** for a rock sample.

- We know the sample is at the surface \((z = 0)\) today, and we can use the **advection velocity** \(v_z\) to determine the cooling history.

- **How?**
Now what?

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**How?**

- We can calculate the **past depth** of a rock sample by using **time steps** back to some time in the past.

- Each time step, the **rock will be displaced by** \(v_z \times dt\).
Generating a thermal history

- At each time, record the depth and temperature, then move the particle upward by $v_z \times dt$

- The result is a thermal history for a given exhumation (advection) rate that can now be linked to an estimated closure temperature to predict a cooling age and compare to data.
General concept for age prediction

1. Calculate thermal solution
2. Generate thermal history based on thermal solution and advection velocity
3. Use thermal history to calculate $T_c$
4. Record time at which sample cools below $T_c$ (predicted age)
5. Compare predicted age to measured age
6. Repeat steps 1-5 as needed until a good fit is observed