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Long-wavelength late-Miocene thrusting in the north Alpine foreland: implications for late orogenic processes

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Text S1
Apatite separation and picking

Electrodynamic disaggregation (selFrag)

To release the apatite crystals from the rock samples, we used the electrodynamic disaggregation technique (selFrag). This method exposes the rock specimen to a high voltage pulse and fractures it along its grain boundaries. As opposed to separation using a jaw crusher, this method is less time consuming and the rock is disintegrated along the grain boundaries (Giese et al., 2010). This ensures that individual grains are less prone to damaging during processing.

To prepare the samples for electrodynamic disaggregation, they had to be crushed into fist-sized pieces by hand using a hammer. This was necessary due to the limiting dimensions of the processing vessel of the selFrag. For releasing the individual grains, we applied a frequency of 3 Hz and electric potentials of 130-150 kV, depending on the hardness of the rock. For every sample, the electrode distance was incrementally reduced in 5 mm steps from a maximum of 40 mm to a minimum of 15 mm. Per step, a minimum of 20 pulses was applied to ensure full release of the individual grains. It has been shown that the influence of diffusive loss of ^{4}He due to the plasma channel hitting the apatite crystal is negligible, and (U-Th-Sm)/He (AHe) ages from samples separated with electrodynamic disaggregation are indistinguishable from AHe ages measured on apatites released with mechanical techniques (Giese et al., 2010).

Apatite concentration

Apatite crystals were concentrated using standard rock separation techniques. First, the grain size fraction of 64-250 µm, which is suitable for AHe dating, was separated using disposable sieving meshes. To remove magnetic minerals from the sieved sample fraction, we used a Frantz magnetic separator at 0.5 A and 1.2 A. To concentrate apatite from the remaining grains, we used lithium-based tungstate (ρ = 2.81 g cm^{-3}) as heavy liquid for density separation of the heavy minerals. On average, we had to process ca. 100 g of sample material to acquire enough heavy minerals. The heavy mineral fraction has been thoroughly rinsed with deionized water and then dried at 30°C.

Apatite picking

Apatites have been hand-picked under a binocular and checked for inclusions and imperfections under an optical microscope with cross-polarized light. Wherever possible, we selected euhedral, intact, and inclusion free grains with a minimum width of 60 µm. However, as the grains are detrital, partly grains with rough surfaces or tiny fluid inclusions had to be picked. This may result in larger error bars or even grain ages that do not yield a geologically meaningful age. These ages were excluded (see section 3.2 and Table 1 in the main text).

Text S2
Shortening estimates for cross-section C-C' in the Lake Thun area

Shortening estimates inferred from thrust angle and depth of AHe closure temperature

For tectonic slices where samples show a fully reset (U-Th-Sm)/He (AHe) ages we can calculate minimum amounts of shortening which were required for the sample to pass through the partial retention zone (PRZ). The latter describes the diffusion-sensitive temperature interval between ca. 80°C and 40°C (Wolf et al., 1996). Using a temperature range of the PRZ of 40°C and assuming a paleo-geothermal gradient G of 28°C/km (Schegg and Leu, 1998) we can estimate a thickness of the PRZ:

$$Z_{PRZ} = \frac{PRZ_{Tmax} - PRZ_{Tmin}}{G}$$

Using a thrust angle α of 25°, we can solve the following equation to calculate ca. 3.2 km of minimum horizontal shortening for a thrust which allows to exhume fully reset ages in the hanging-wall of the thrust:

$$s_h = \frac{z_{PRZ}}{\tan(\alpha)}$$

East of the Aare valley, where we have a robust set of AHe ages, we can identify a frontal thrust (T2) which was active at ca. 10 Ma and an out-of-sequence thrust (T3) which was active at ca. 6 Ma (Fig. S1). Analogous to the situation west of the Aare valley, we can assume that the southernmost thrust (T1), along which Rupelian deposits were thrusted on top of Chattian-Aquitanian deposits, was active at ca. 11 Ma. Hence, for each thrust to produce fully reset ages in their hanging-walls, we can infer for each a minimum horizontal shortening of ca. 3.2 km, which results in a minimum amount of cumulative horizontal shortening of ca. 9.6 km.

Cross-section restoration

Figure S1 shows a balanced cross-section across the Subalpine of the Lake Thun area. We restored the cross-section using the Move Software Suite (Petroleum Experts Limited). Since hanging-wall cut-offs of the thrusts, which show the largest displacements, are not preserved, we retro-deformed the cross-section until the bedding of the Molasse deposits was sub-horizontal. Further uncertainty arises from the fact that the southward continuation of the thrusts is not constrained. In order to retro-deform, we extended the thrusts as being shallow southward dipping. Using these assumptions, we can infer that thrusts T2 and T3 accommodate a minimum of ca. 11.3 km of cumulative horizontal shortening. When also considering thrust T1, along which Rupelian deposits were thrusted on top of Chattian-Aquitanian deposits, retro-deformation yields an additional ca. 9 km of horizontal shortening in order to restore the Rupelian deposits to its original position on top of the Mesozoic strata. Shortening accommodated by the thrusts north of T2 is very minor and neglectable.

From cross-section balancing, we can infer a total of ca. 20 km of horizontal shortening. However, only ca. 9.6 km of late Miocene shortening accommodated by thrusts T1, T2, and T3 are necessary to produce the observed fully reset AHe ages. Therefore, we can infer that late Miocene shortening along the balanced cross-section ranges somewhere between ca. 9.6 – 20 km.

Figure S1

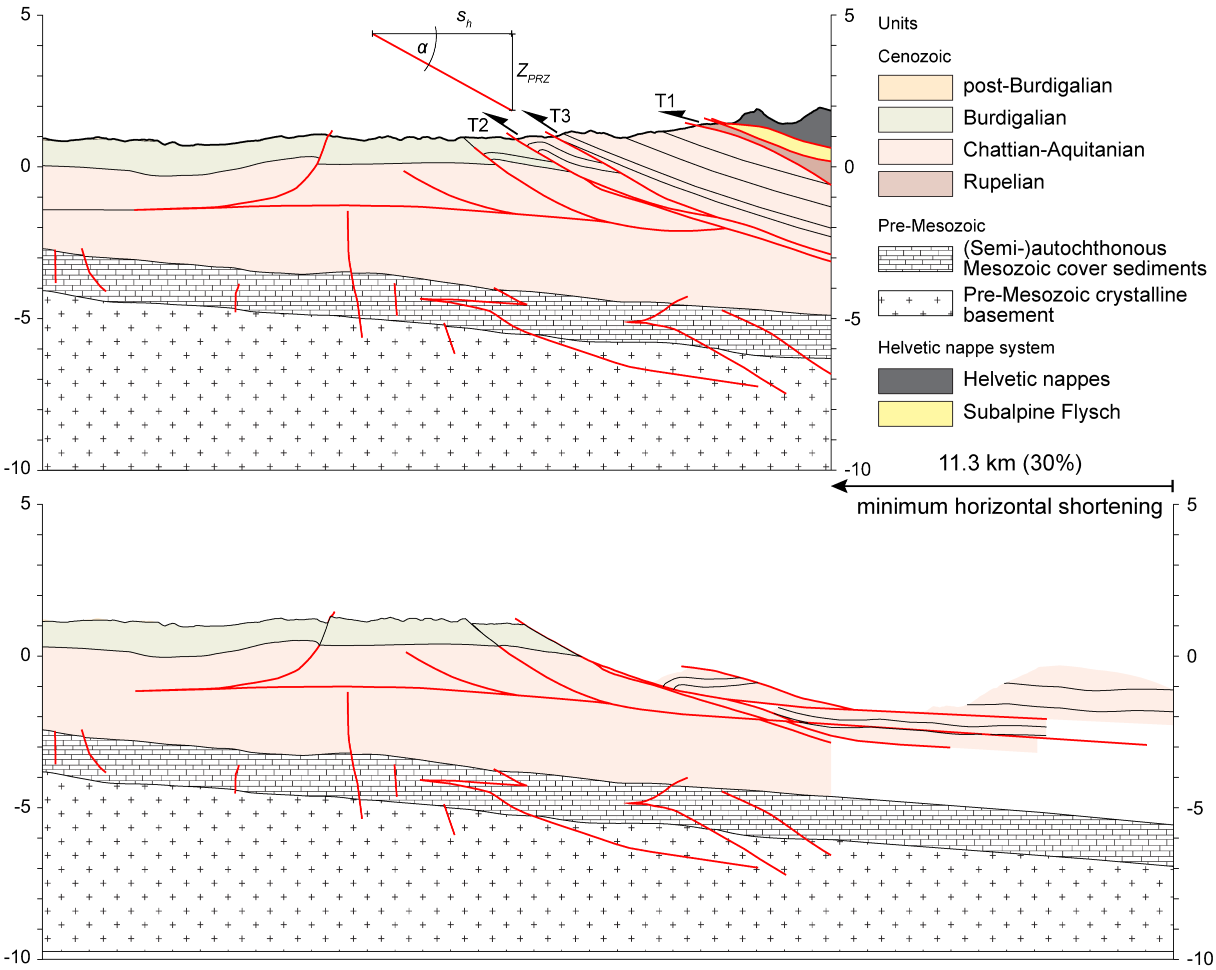

Fig. S1 Restored cross-section through the sampling area east of the Aare valley (location of this section is given in Fig. 3a of the main text).

References

Giese, J., Seward, D., Stuart, F.M., Wüthrich, E., Gnos, E., Kurz, D., Eggenberger, U., and Schreurs, G., 2010, Electrodynamic Disaggregation: Does it Affect Apatite Fission-Track and (U-Th)/He Analyses? Geostandards and Geoanalytical Research, v. 34, p. 39–48, doi: 10.1111/j.1751-908X.2009.00013.x.