Measuring changes in orogenic taper through time using low-temperature thermochronometry

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1. Overview

Introduction

The question of quantifying surface uplift of an orogen through time has been long outstanding. In this contribution, we show that it is possible to constrain the changes in orogenic taper (i.e. a combination of surface and basal detachment slope) on a million year time scale, combining low temperature thermochronology with critical wedge dynamics.

We selected the Central European Alps (Figure 1) as suitable study area, due to the unparalleled amount of geological and structural data and the well studied present day kinematics. Additionally, countless studies document their exhumation history.

We report apatite fission track and apatite (U-Th)/He data from profiles across the Subalpine Molasse, which forms the southern, folded and thrusted part of the foreland basin and is as such a key element, linking the Alps with their foredeep. We use these data to reconstruct the kinematic evolution of the Central Alpine wedge since 10 Ma.

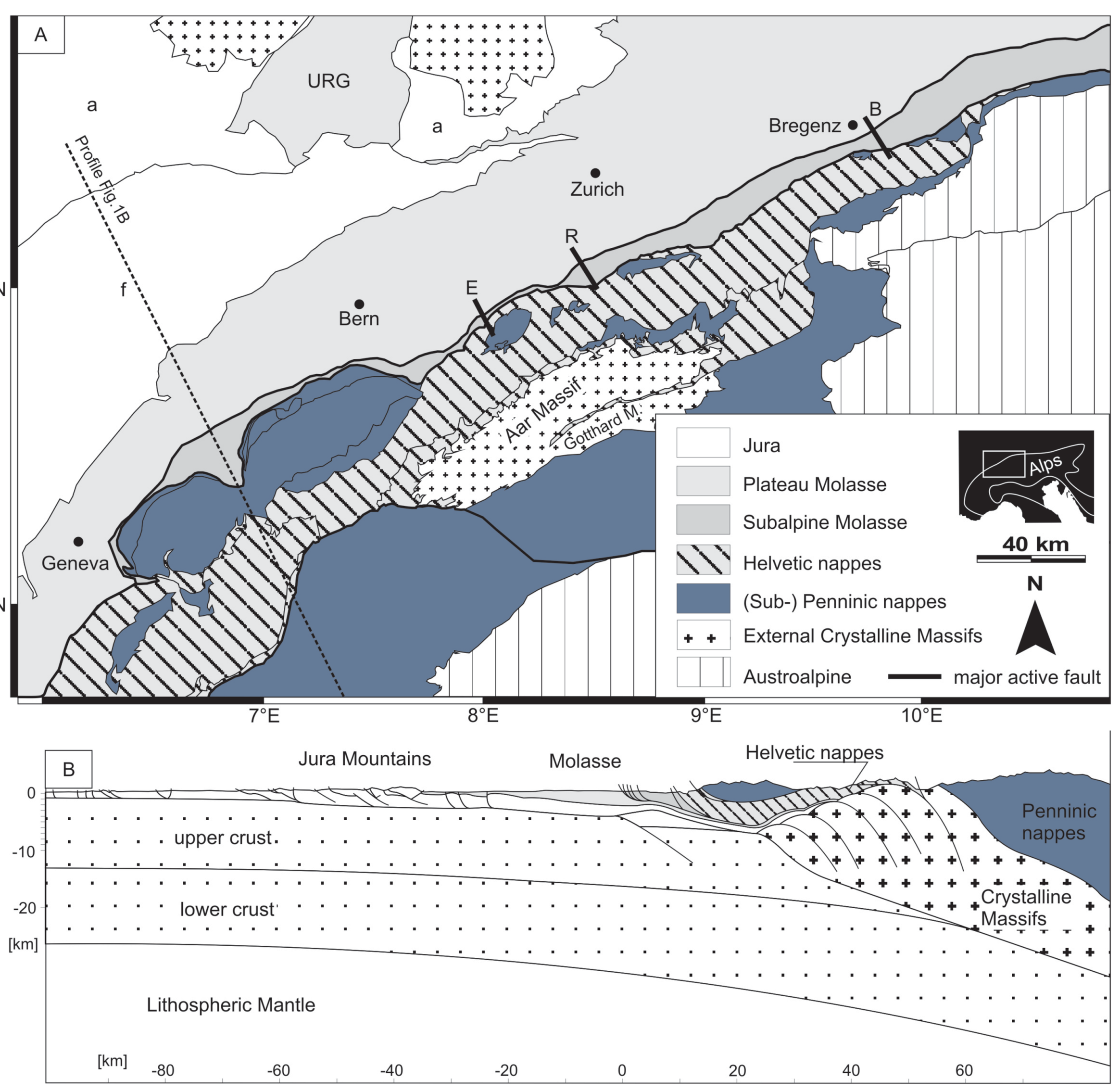


*Figure 1: **Tectonic map of the Northern Central Alps and the adjacent foreland** based on Spicher (1980). URG – Upper Rhine Graben, a – autochthonous Jura, f – folded Jura, traces of analyzed profiles indicated by black lines. Note the crystalline bodies within the Alps, the External Massifs (including the Aar Massif). Figure 1B is a cross section through the Central Alps, modified after Burkhard and Sommaruga (1998), showing all major tectonic units. The origin of the x-axis is located at the northernmost thrust of the Subalpine Molasse. The limit of seismicity and the 300-350 °C isotherm is based on Okaya et al. (1996).Note that the Jura Mountains, the Subalpine Molasse and the External Massifs are linked through the same detachment.*

2. Thermochronometry

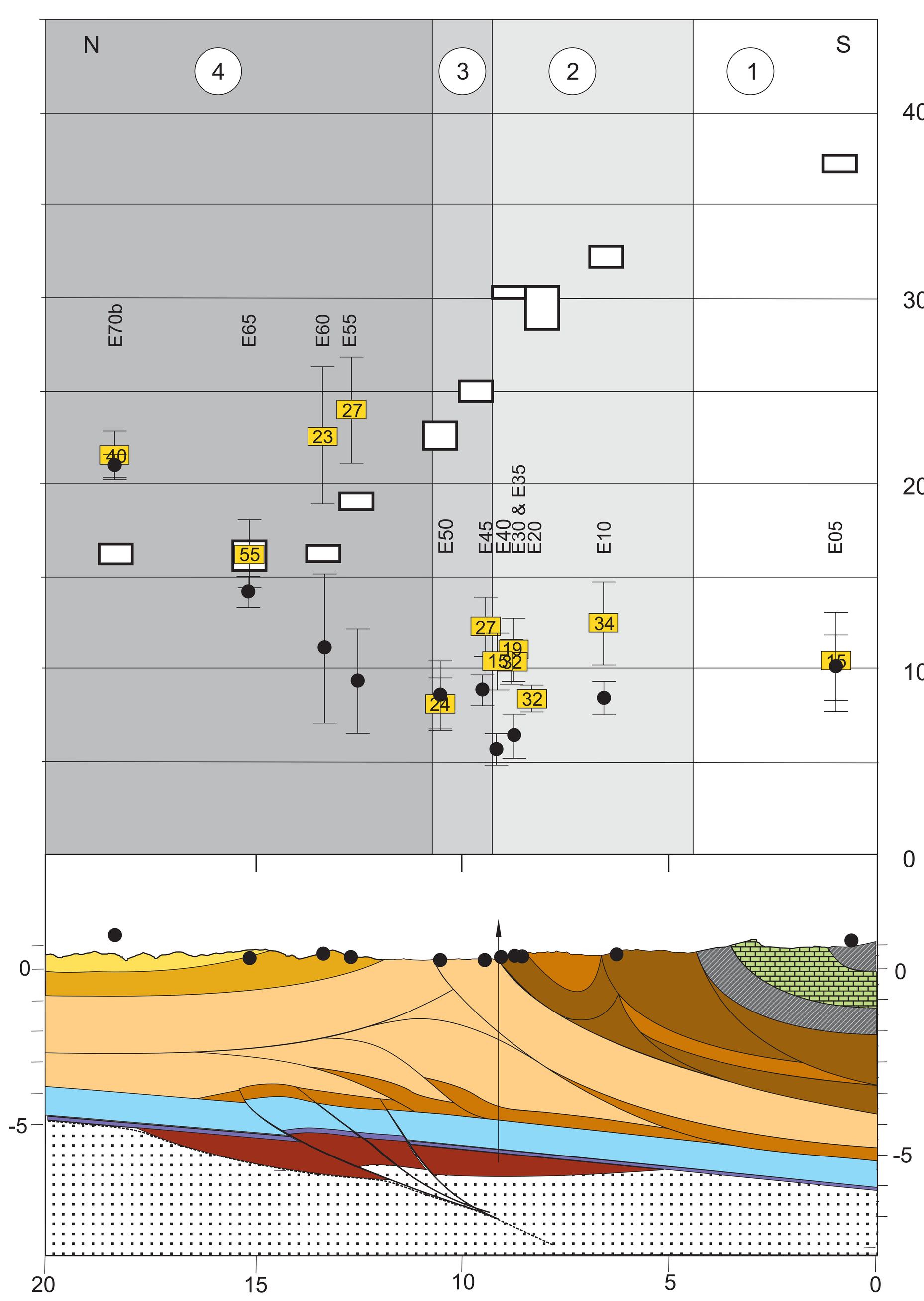


*Figure 2: **Entlebuch cross section across the Subalpine Molasse (SM) south of the Jura Mountains** (profile 'E' in Figure 1). Thermochronological ages projected into the profile and plotted above. Different shades of grey denote different tectonic slices (TS), which can be followed along strike the entire Central Alps*

*This profile is characterized by young AFT ages in the southern part, and ages which are older than depositional age in the North. The crossing point, i.e. the exhumed PAZ/PRZ, lies at the northern termination of the triangle zone **Note the offsets in AFT and AHe ages across the thrusts between TS-2 and TS-3 and TS-3 and TS-4.***

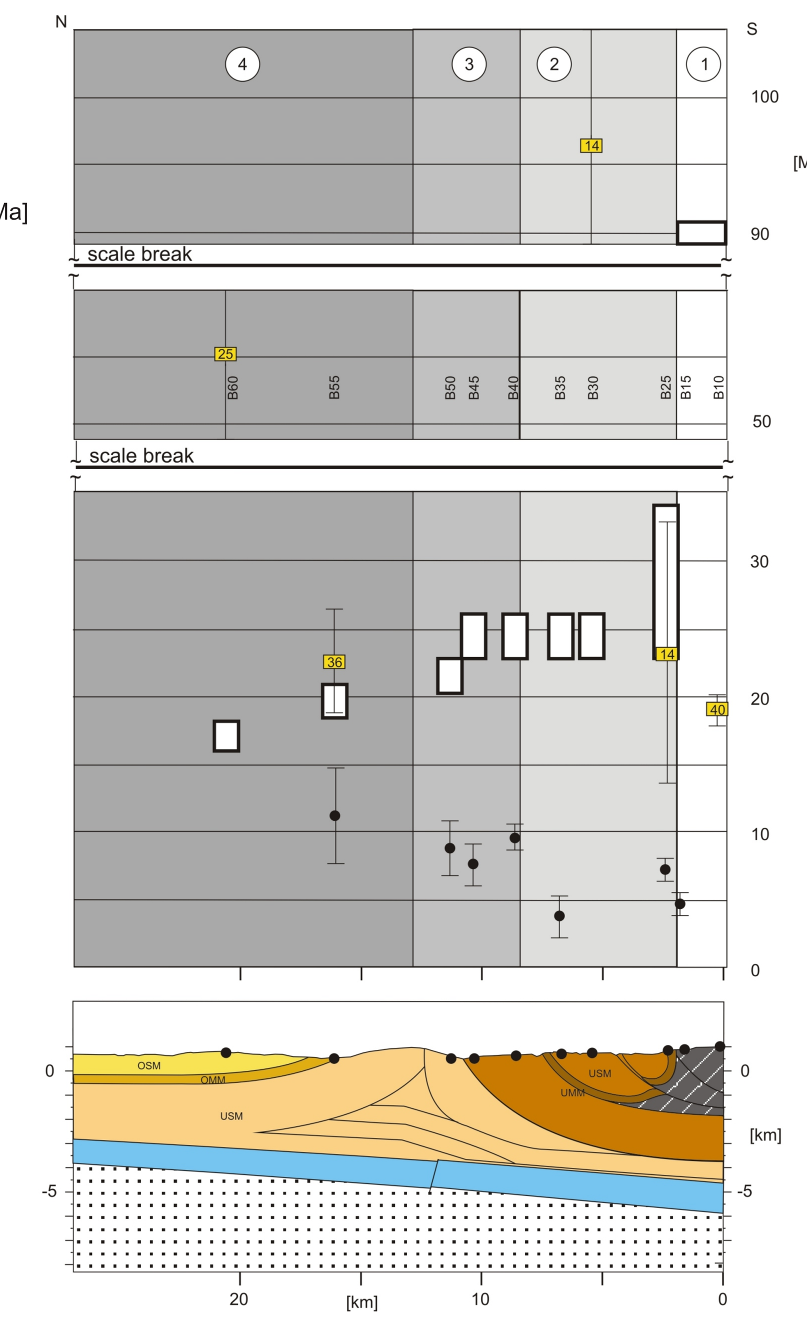


*Figure 3: **Balanced cross section across the SM south of Bregenz, Austria** (profile 'B' in Figure 1). Black dots indicate the projected data points. **Note the offsets in AHe ages across the thrusts between TS-1 and TS-2.***

We can detect a minimum of 20 km of post 10 Ma north-westward displacement of the Aar Massif on the basal décollement. We can use that for restoring the Late Miocene wedge geometry by combining it with its exhumation history

3. Neogene shortening

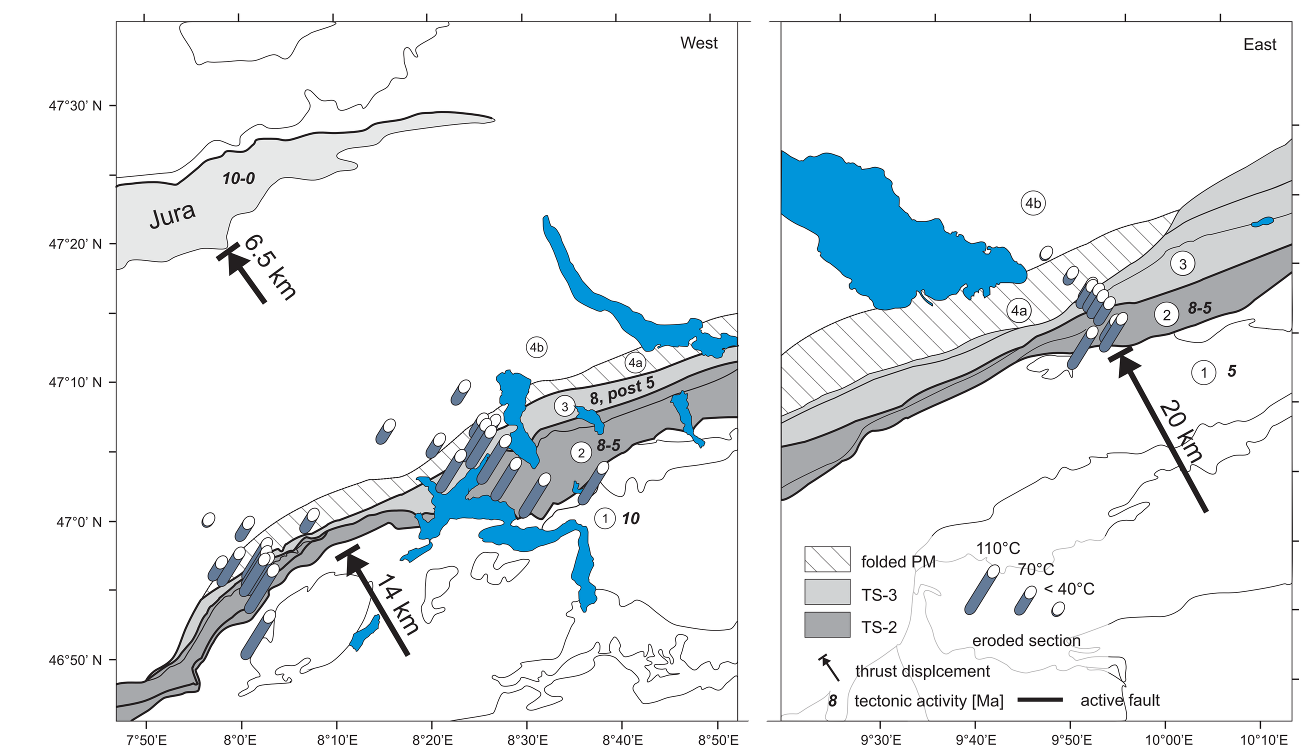


*Figure 4: **Comparison between thermochronological data in the Subalpine Molasse.** Left panel shows data from south of the Jura Mountains (JM), right panel from east of the JM. Note the similarities in thrust activity and amount of thrust displacement. Data from the JM taken from Bollinger 1993 and Madritsch et al. 2010*

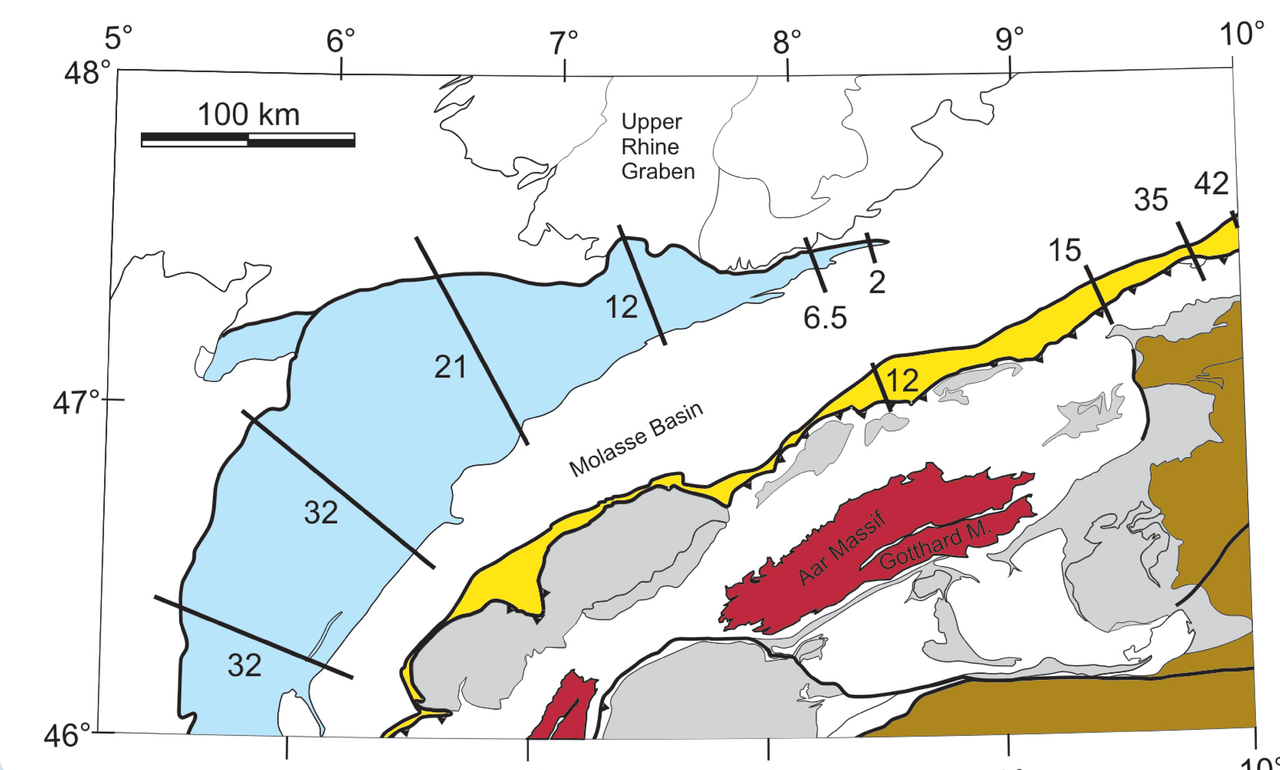


*Figure 5: **Neogene shortening within the Central Alps** (based on Schmid et al. 2004). Shortening in the Jura taken from Philippe (1996), shortening within the Subalpine Molasse compiled from Schmid et al. (2004), Frisch et al. (1998) and v.Hagke et al.(2012). Using the respective detachment dips, we can translate these values into thrust displacement (see also Figure 4)*

4. Palaeo-taper

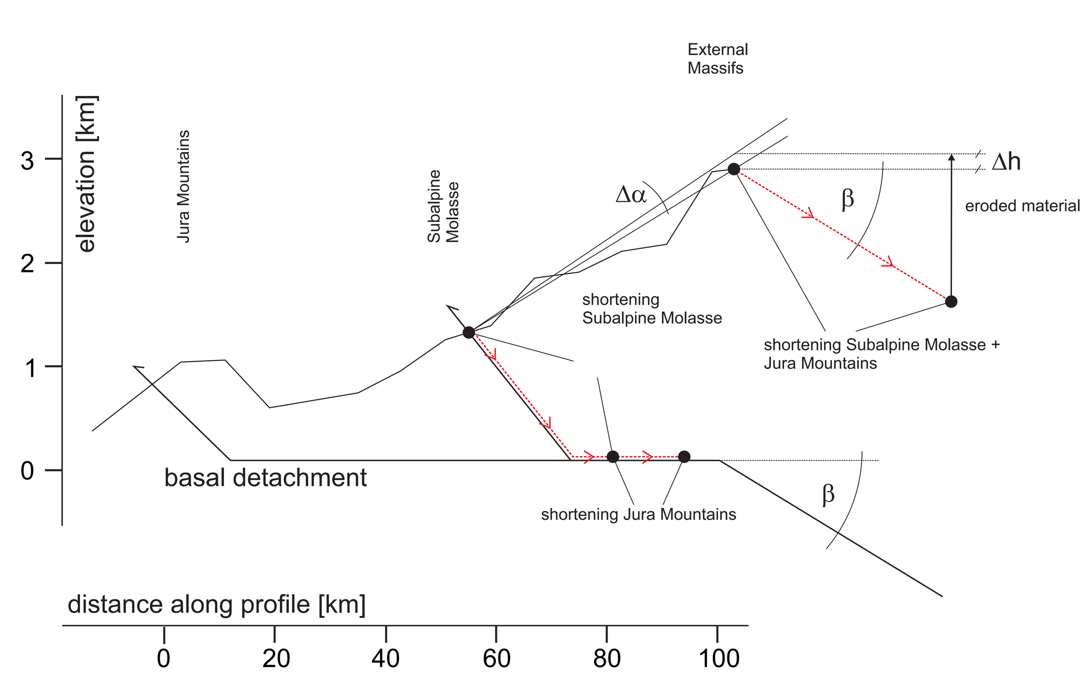


*Figure 6: **Sketch of the restoration of the wedge taper since 10 Ma.** We can use exhumation calculations from the Aar Massif to restore the pro-wedge geometry at 10 Ma and consequently detect whether the taper of the pro-wedge has varied substantially within that time frame. For the western part, we consider a material point at the surface of the Aar Massif and restore it by 20.4 – 20.8 km of post 10 Ma slip on a detachment ramp dipping 19° and then restore the measured exhumation.*

In a second step, we calculate Δh by subtracting these values from reported exhumation values. Using small angle approximation (sin Δα ≈ Δα), the difference in taper Δα can be calculated measuring only the distance between the Jura Mountains and the External Massifs.

***The change in taper angle (Δα) since 10 Ma is the difference between present-day surface taper angle and the taper angle resulting from restoring the material point** (tables 1 and 2).*

Measured exhumation [km]	Δ h	Distance along profile = 85 km	Distance along profile = 90 km	Distance along profile = 95 km
5	0.16	0.11	0.10	0.10
5	-0.97	-0.66	-0.62	-0.59
5.6	0.76	0.51	0.48	0.46
5.6	-0.37	-0.25	-0.24	-0.22
6.4	1.56	1.05	0.99	0.94
6.4	0.43	0.29	0.27	0.26
12	7.16	4.81	4.55	4.31
12	6.03	4.06	3.83	3.63

*Table 1: **Differences in orogenic taper since 10 Ma for the western profile**. Measured exhumation calculated from pubnlished exhumation rates by Reinecker et al. (2008), Michalski & Soom (1990), Weisenberger et al. (2012), Vernon et al. (2009), Glotzbach et al. (2010) and Valla et al. (2012). Δh is the difference between estimations of exhumation and the required exhumation to maintain taper. Δα-values are highlighted in red.*
***All Δα values are (sometimes considerably) lower than 1°**, exept for the calculations with 12 km of exhumation, which do not seem to be geologically reasonable.*

Measured exhumation [km]	Δ h	Distance along profile = 45 km	Distance along profile = 50 km	Distance along profile = 55 km
5.4	1.35	1.72	1.55	1.41
5.4	-0.23	-0.30	-0.27	-0.24
5.4	0.03	0.04	0.04	0.03
5.4	-1.68	-2.14	-1.93	-1.75

*Table 2: **Differences in orogenic taper since 10 Ma for the eastern profile.** Thrust displacement values used are 20 and 22 km, derived from our section balancing. The grey fields are calculated with a décollement dip of 17°, the red fields are calculated with a décollement dip of 21° due to a less well constrained detachment as compared to the west.*

These values show that the taper in the Central Alps did not change within uncertainty.

5. Kinematic steady state

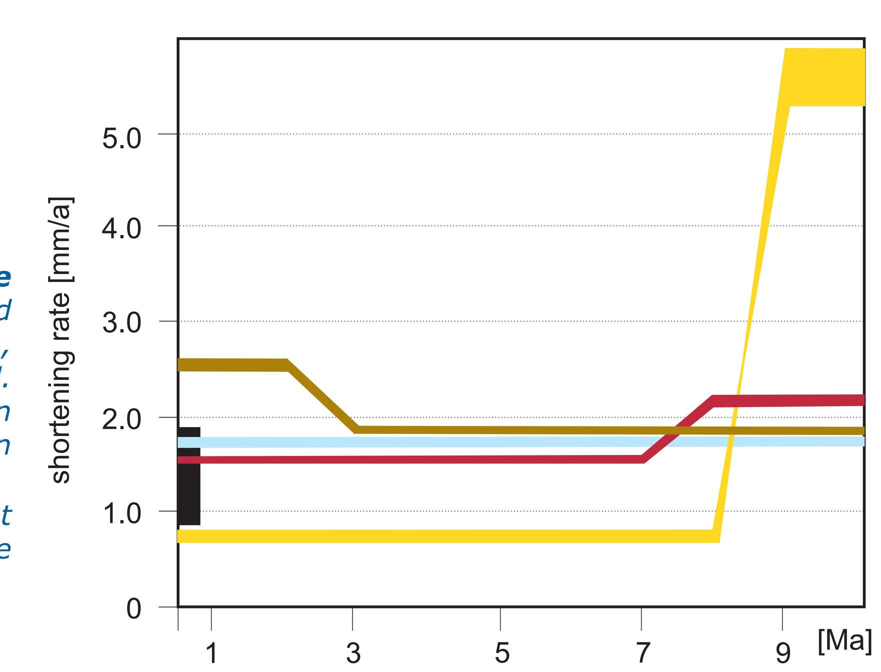
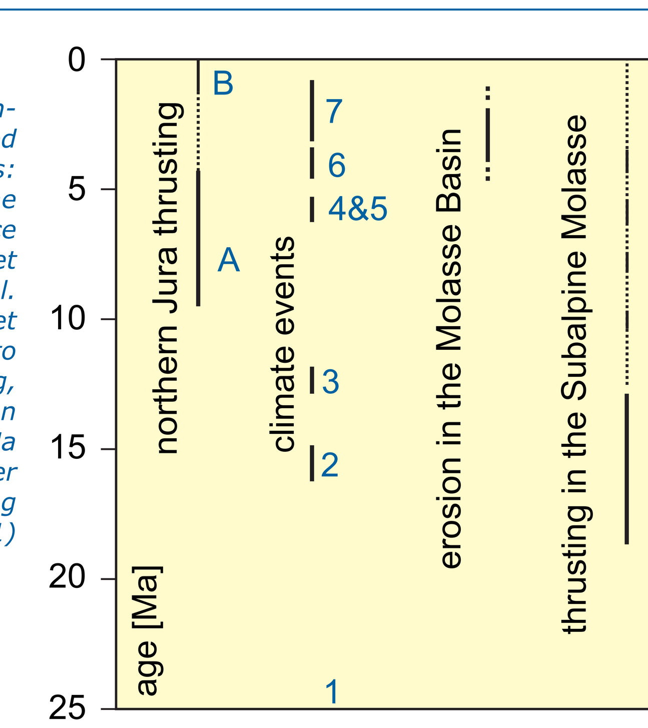


*Figure 7: **individual shortening scenarios for the reported exhumation rates**. The finding of constant taper geometry since 10 Ma implies that uplift of the Aar Massif is largely controlled by the above determined displacement magnitudes over a major crustal scale ramp (see Fig. 1B). Therefore, we assume that exhumation rates are directly proportional to shortening rates and we can estimate the evolution of shortening rates through time on the base of the reported exhumation data. Michalski and Soom (1990), Reinecker et al. (2008) and Weisenberger et al. (2012) – (blue), Valla et al. (2012) (yellow), Glotzbach et al. (2010) (red) and Hurford et al. (1989) (brown). The black rectangle denotes the possible range of present day shortening rate within the Central Alps (Champagnac et al., 2009, von Hagke et al, in rev.).*

A fundamental consequence of these considerations is that present day shortening within the Central Alps is necessary to satisfy the data from the foreland and the External Massifs.

*Figure 8: **Timing of events in the Alpine foreland basin.** A: thin-skinned Jura thrusting after Bollinger et al. (1993), B: thick skinned thrusting after Becker (2000), Madritsch (2008, 2010). Climate events: (1) Late Oligocene Warming (Mosbrugger et al. 2005), (2) Mid-Miocene Climatic Optimum (Mosbrugger et al. 2005), (3) East Antarctic Ice Sheet (Bruch et al. 2007), (4) Alpine glaciation at 6.26-5.50 (Hodell et al. 2001), (5) Messinian Salinity Crisis at 5.96-5.33 (Krijgsman et al. 1999), (6) increased global climate perturbation since 3.8 Ma (Zhang et el. 2001) and gradual increase in moisture supply in Europe due to closure of the Panama Isthmus from 4.6-3.2 Ma (Driscoll and Haug, 1998, Cederbom et al. 2004), (7) Northern Hemisphere Glaciation starting at 3.1-2.5 Ma and reaching its maximum at c. 1.0-0.8 Ma (Haeuselmann et al. 2007). Erosion in the Molasse Basin after Cederbom et al. (2011) and Willett and Schlunegger (2010). Thrusting in the Subalpine Molasse after Trümpy (1980), Cederbom et al. (2011) and von Hagke et al. (2012).*



Conclusions

➲ **the shortening rates for the northern flank of the Central Alpine pro-wedge are constant since at least 8 Ma and fall between 1 and 2 mm/a**

➲ **the taper angle of the Central Alps did probably change no more 1° since Late Neogene times**

➲ **the Central Alps are at kinematic steady state since at least 8 Ma**

➲ **the mass flux between erosion and accretion in the pro-wedge is at steady state**

➲ **we have no evidence that Miocene to Pliocene climatic events influenced the wedge stability and kinematics on the northern flank of the Central Alps**

➲ **combining thermochronometry with critical wedge dynamics is a powerful tool to understand mountain building and the governing processes**