Late Miocene to present deformation and erosion of the Central Alps — Evidence for steady state mountain building from thermokinematic data

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ABSTRACT
We present new apatite fission track and apatite (U-Th)/He data from the Alpine orogenic front, the Austrian Subalpine Molasse. We show that the cooling signal reported from the Swiss part of the basin since 10 Ma is also present farther east. Hence, it appears to be independent of the kinematic relation to thrusting in the external thrust belt present further west, the Jura Mountains. By reconstructing the Central Alpine pro-wedge geometry at 10 Ma, we show that the taper of the Central Alps has not changed significantly and presumably remained close to the critical state since then. From cooling offsets at faults, the present day shortening rate of the pro-wedge ranges between 1.0 and 2.0 mm/a and appears to have been constant since at least the Late Miocene. In conjunction with the observations of repeated out-of-sequence thrusting in the Subalpine Molasse, a stationary deformation front, constant shortening and erosion rates and the constant taper, we argue that the Central Alpine pro-wedge is at kinematic, as well as at mass flux steady-state since 10 Ma. Our results suggest that distinct climate-driven erosion events — in contrast to more continuous erosion — are not distinguishable in the deformation record of the last 10 Ma. Hence, kinematic and mass flux steady state in the Central Alpine pro-wedge along with stable localization of deformation restricted to the Subalpine Molasse may indicate a feedback between ongoing shortening and erosion at low rates during the Late Neogene to present.

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1. Introduction
Orogenes are the result of complex interactions between tectonic and climatic processes, which are coupled through erosion. To understand these dynamic systems, it is vital to quantify how orogens evolve through time, in order to assess how potentially climate-driven changes in erosion rate have changed orogen dynamics. Being one of the most studied orogens in the world, the European Alps provide an exceptional dataset to contribute to our understanding of mountain building, and the coupling between climate and tectonics. Yet, contrasting hypotheses exist whether they reached steady state since at least the Late Miocene (e.g. Bernet et al., 2001; Glotzbach et al., 2010), or if climatic changes resulted in increased erosion rates and consequent tectonic pulses (e.g. Cederbom et al., 2004; Kuhlmann and Kempf, 2002; Willett et al., 2006). The lack of understanding of the Late Miocene to present tectonic history of the Alps and its foreland is mostly due to erosional removal of foreland sediments of that time. Reconstruction of the kinematic history remains problematic, as it usually hinges on such foreland deposits. We here use low-temperature thermochronology as a means to retrieve the exhumation history of an orogen despite the incompleteness of foreland sediments. Extensive data sets exist for much of the European Alps (e.g. Glotzbach et al., 2010; Hurford et al., 1989; Michalski and Soom, 1990; Reinecker et al., 2008; Valla et al., 2012; Weissenberger et al., 2012), and parts of their foreland (e.g. Cederbom et al., 2004, 2011; Mazurek et al., 2006; von Hagke et al., 2012). In this study, we show that it is possible to reconstruct the kinematic evolution and taper of an eroded mountain belt front through time, combining thermochronological data with a wedge-mechanical model. We focus on the central part of the orogen (Fig. 1), commonly referred to as the Central Alps, because along strike variations in deep structure and timing of metamorphic events are small enough to suggest along strike consistency of wedge dynamics (Gebauer, 1999; Schmid et al., 2004).

2. Geological framework
Late stage orogeny of the European Alps during the Neogene saw the development of a classical orogenic foredeep — the Molasse basin —
resulting from flexural bending of the European plate by the advancing orogenic wedge (Burkhard and Sommaruga, 1998; Pffiffer, 1986; Pffiffer et al., 2002; Schlunegger et al., 2007; Sinclair et al., 1991). At the southern fringe of the basin, Rupelian to Serravallian (c. 35–11 Ma) sediments became part of the Alpine wedge shortly after deposition (Homewood et al., 1986; Kempf et al., 1999; Pffiffer et al., 1997; Sinclair and Allen, 1992). This lead to formation of the folded and thrust Subalpine Molasse, often with a characteristic triangle zone (Müller et al., 1988; Vollmayr and Wendt, 1987) (Fig. 2). At c. 10 Ma, folding of the Jura Mountains in an external position started in the western Central Alps (e.g. Bollinger et al., 1993; Burkhard, 1990; Burkhard and Sommaruga, 1998), coeval with the onset of uplift and exhumation of the External Crystalline Massifs (Fügenschuh and Schmid, 2003) (Fig. 1). At the same time, the drainage divide which defines the Neogene Central Alpine pro-wedge formed by the uplifting External Massifs. East of Zürich, no external Jura type fold belt exists. Here, the Bavarian Molasse Basin forms the most external Alpine unit, and the basal décollement of the Subalpine Molasse terminates at the present day orogenic front. The spatial extent of the Jura Mountains and its lateral limitations correlates with the existence of evaporites of Permian and Triassic age at depth (Laubscher, 1961, 1977; Philippe et al., 1996). Exhumation of the Aar Massif is well constrained by several thermochronological studies, including the eastern part of the Central Alps, where the Aar Massif is still covered by the Silvretta Nappe (Glótzbach et al., 2010; Hurford et al., 1989; Michalski and Soom, 1990; Reinecker et al., 2008; Valla et al., 2012; Weisenberger et al., 2012). Likewise, thermochronological data exists from the western part of the Central Alpine foreland, constraining exhumation mostly

Fig. 1. A: Tectonic map of the Northern Central Alps and the adjacent foreland based on Spicher (1980), modified from von Hagke et al. (2012). URG: Upper Rhine Graben. We restore the Central Alpine wedge along two cross sections, one including shortening within the Jura Mountains (profile Fig. 4), and one in the eastern part of the study area, along profile Fig. 2 and its southward prolongation. Samples were collected along the latter. B: profile across the Alps modified after Burkhard and Sommaruga (1998). This profile is similar to published profiles from the eastern part of the Central Alps (Pffiffer and Hitz, 1997; Schmid et al., 1996), showing consistency along strike, and the link between exhumation of the Aar Massif and foreland shortening.

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south of the Jura fold and thrust belt. These studies show that deformation in the Subalpine Molasse continued after 5 Ma (Cederbom et al., 2004; Cederbom et al., 2011; Mazurek et al., 2006), hence during times when the Jura Mountains were actively deformed (von Hagke et al., 2012). Interpretation of seismic lines and section balancing shows that the Aar Massif, the Subalpine Molasse and Jura Mountains are linked via a common detachment (e.g. Boyer and Elliott, 1982; Pfeiffer et al., 1997). The latter steps down into the middle crust at a...
major ramp underlying the Aar Massif. Accordingly, deformation in the Subalpine Molasse and in the Jura Mountains is directly related to uplift and exhumation of the Aar Massif in the Central Alps. For understanding exhumation of the Central Alpine wedge, it remains to be tested whether the exhumation signal reported from the western part of the foreland persists along strike the Central Alps, and if shortening occurs on the same detachment system. Accordingly, we first present a new low-temperature thermochronological dataset from the eastern Central Alps, and then restore the geometry of the Alpine wedge since the Late Miocene along two cross sections (Fig. 1), combining new with previously published data.

3. Thermochronological methods

Apatite fission track (AFT) and apatite (U-Th-Sm)/He (AHe) dating allow reconstructing the tectono-thermal history of the topmost few kilometers of the earth's crust. A combination of these two methods has proven to be a powerful means for deciphering low-temperature cooling histories (Armstrong et al., 2003; Stockli, 2005), especially when syntectonic sediments are missing due to late stage erosion as is the case in the North Alpine Foreland Basin. These dating methods are sensitive to cooling intervals between ~120–60 °C and ~80–40 °C, respectively (Carlson et al., 1999; Wolf et al., 1996). These temperature intervals are termed the partial annealing zone for the AFT system and partial retention zone for the AHe system, respectively. Reheating of an apatite grain during burial within the foreland leads to successively younger apparent ages, and eventually completely resetting of the respective thermochronological clock. For instance reheating to 90 °C will completely reset the AHe system, but only partially reset the AFT system. Additionally, apatite grains may have different annealing kinetics, e.g. due to different chemical composition, and will hence reset at different temperatures within the same system (Carlson et al., 1999), which leads to different grain age populations in partially reset samples. Thermochronological ages from foreland basin sediments that are older than their stratigraphic ages provide information about the cooling of the hinterland, and constrain the maximum temperature reached in the basin. For detailed description of the methods, the reader is referred to Donelick (2005) for fission track dating and Farley and Stockli (2002) for (U-Th-Sm)/He dating.

Sample preparation for AFT dating was carried out according to the methods described by Donelick et al. (2005). To analyze uranium concentration, we used laser ablation inductively coupled plasma mass spectrometry (Donelick et al., 2005; Hasebe et al., 2004). Samples were ablated with a New Wave UP-213 laser ablation system; elements were analyzed in solution with a Finnigan Element2, i.e. a high-resolution single collector ICP-MS. We performed all laser ablation analyses at the GeoAnalytical Lab of Washington State University, in the USA. Central and peak ages were calculated with the RadialPlotter software (Vermeech, 2009). We determined Dpar for all single grains. This is a measure of annealing kinetics, with lower Dpar values indicating higher sensitivity to annealing (Carlson et al., 1999; Ketcham et al., 1999). For AHe analysis, apatites were analyzed with a SteREODiscovery V12 microscope with a Plan S 1.0× objective. The microscope is equipped with cross-polarizer, rotating stage and plane-polarized darkfield illumination at 100×. We selected at least three grains for every sample. The grains were degassed and analyzed for parent isotope content in the laboratory of the University of Kansas. Raw AHe ages were corrected for alpha ejection at the crystal surfaces after Flowers et al. (2009). The weighted mean AHe ages account for broken grains and consequent uncertainties of the fs corrections (Brown et al., 2011; Fitzgerald et al., 2006).

4. Structural and thermochronological data, and post-10 Ma tectonic activity of the Subalpine Molasse

In the western part of the Subalpine Molasse we identified four structural domains (or tectonic slices, TS), which are bounded by fault contacts, and have been tectonically active in the past 10 Ma (von Hagke et al., 2012). The limits of these tectonic slices are thrusts which run parallel to the Alpine front over long distances, whereas faults within these tectonic slices are generally only of local importance. TS-1 represents all analyzed units south of the basal Alpine thrust. The northern limit of TS-2 is the basal UMM thrust, which also forms the southern limit of the triangle zone. TS-3 is the triangle zone itself, and TS-4 represents the mostly flat lying Plateau Molasse (Fig. 2). We selected the Bregenzerach section for structural analysis and thermochronological age dating, because it is one of the few profiles that provide excellent outcrops in all tectonic units of the Molasse east of the extent of the Swiss Jura Mountains (see Fig. 1 for location). Furthermore, exhumation data from the units within the orogen is available (Hurford et al., 1989). This data set comes from the Austraoline units, which overlie the Aar Massif. This cross section can be directly compared to the cross section farther west (see above). Fig. 2 shows a new balanced cross section. We can deduce a total of 32 km of horizontal shortening in the exposed part of the Subalpine Molasse. This estimate is consistent with estimates of more than 30 km from an adjacent balanced profile (Müller, 1984). Line length balancing reveals that the frontal triangle zone accommodates 12 km of shortening. The remaining 20 km occurred in a break-back thrust sequence thereafter, and thus later than 9 Ma, because deformation of the triangle zone outlasted deposition of the youngest preserved sediments (~9 Ma; Eberhard, 1986).

We obtainedapatite fission track (AFT) and apatite (U-Th)/He (AHe) data from every tectonic slice within the cross section (TS-1 to TS-4, Fig. 2). We report all fission track data in Table 1, peak ages in Table 2, and the single grain and mean AHe ages in Table 3. In TS-1, the obtained central AFT age (sample B10) is 18.6 ± 1.7 Ma, AHe dating (sample B15) yielded a weighted mean age of 5.0 ± 0.7 Ma. Both ages are considerably younger than their corresponding stratigraphic age, which requires substantial reheating after deposition. In TS-2, the southernmost sample (B25) yields a central AFT age of 23.5 ± 9.7 Ma, which can be decomposed into two grain age populations (Table 2), indicating partial resetting. Further north, sample B30 yields a central fission track age of 96.4 ± 17.7 Ma with a youngest peak age of 35.1 Ma, which is still older than the corresponding stratigraphic age. The AHe ages of TS-2 in contrast are younger than the corresponding stratigraphic ages, indicating complete resetting of the AHe system. In the south, sample B25 yields an age of 7.6 ± 0.57 Ma, which is older than the age of the adjacent sample B15, south of the thrust. In the north, sample B35 yields an age of 4.3 ± 1.5 Ma.
which is as young as the AHe age of sample B10. Crossing northward into TS-3, we observe a clear jump in AHe ages. Samples B40, B45 and B50 yield ages of 9.1 ± 0.7, 7.2 ± 2.0 and 8.6 ± 2.5 Ma, thus all reproducing for TS-2. Note that sample B40 is only based on one grain age measurement (Table 3). In TS-4, the central fission track ages and all peak ages are older than their corresponding stratigraphic ages (samples B55 and B60). The mean AHe age obtained from B55 is 10.8 ± 4.2 Ma, which is younger than its corresponding stratigraphic age. However, the broad spread in single grain ages may indicate partial resetting of the sample. All measured Dpar values for the AFT ages are lower than 1.4 μm, indicating complete annealing of fission tracks at temperatures of less than 100 °C (Carlson et al., 1999; Donellick et al., 1999).

Forward modeling with HeFTy shows that reheating to at least 80 °C experienced were high enough to affect the AFT system substantially. Cross section tracks at temperatures of less than 100 °C (von Hagke et al., 2012). Hence, these kinematics are a regional feature that is independent of the proximity of the Jura belt and its underlying evaporate-controlled detachment.

At the Alpine front in the Swiss Alps, von Hagke et al. (2012) estimate 13.9–14.3 km of cumulative displacement from individual surface breaking thrusts to translate onto the Alpine basal thrust. In the northward prolongation of their data set, Philippe et al. (1996) calculate post-10 Ma shortening of 6.5 km within the eastern Jura Mountains on a flat detachment. Since the slip on both sub-horizontal detachments feeds into north-westward displacement of the frontal Aar Massif on the basal detachment in the western Central Alps, this sums up to a minimum of 20.4–20.8 km of post-10 Ma shortening with equivalent NW- and upward translation of the Aar Massif. This is equal to our estimate for the balanced cross section in the east (see above), showing that within the Central Alps total post-10 Ma shortening was similar along strike. However, in the east, all shortening is partitioned in a single detachment below the Molasse, as no Jura-style deeper detachment is present. Additional shortening within the Helvetic domain in the west (Switzerland) is unlikely, since these thrusts do not link with the current detachment but rather form a major klippe with an emergent detachment on both flanks (e.g. Pff hrner, 1993). In the east (Austria), little is known about reactivation of the Helvetic detachment that, here, still roots in the European basement covered by the Austroalpine units (Gebrande et al., 2002). We consider the above estimates to be minimum estimates, as a few percent shortening might be hidden in the gentle folding of the Plateau Molasse (Hindle and Burkhard, 1999), as well as some fold thickening in the Helvetic domain.

Since foreland deformation is kinematically linked with uplift and displacement of the Aar Massif in the hinterland (see above), the amount of thrust displacement within the Subalpine Molasse plus the thrust displacement in the Jura Mountains in the west is balanced by northward displacement of the Aar Massif on its basal detachment. Northward displacement of the Aar Massif across the underlying ramp is directly related to its exhumation. In the following, we use the post-10 Ma exhumation history of the Aar Massif in combination with the shortening estimates from the foreland, in order to restore the Late Miocene pro-wedge geometry. We restore the wedge along two profiles; one located in the west, reaching from the Jura Mountains across the Subalpine Molasse into the Aar Massif, the second one east of the Jura Mountains, along the Bregenzerach (Fig. 2), which is here still covered by Austroalpine units.

5. Restoration of the Late Miocene pro-wedge geometry

We first restore the western cross section, which includes shortening in the Jura Mountains. 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 (as previously determined, see above) on a detachment ramp dipping 19° (Burkhard and Sommanarga, 1998). Resulting uplift of the present day surface of the Aar Massif ranges between 6.6 km and 6.8 km, for the above total displacement and time window. In a subsequent step, we consider the amount of erosion as found in AFT studies. Exhumation of the Aar and Gotthard Massifs in Switzerland is constrained by several studies. Reinecker et al. (2008) report constant exhumation of 0.5 km/Ma at the front of the orogenic wedge. For the western pro-
cacement data from (Cederbom et al., 2011). Corresponding correction factor, excluded ages have not been taken into account for the geological interpretation because of analytical errors or lack of uranium.

Table 3

Apatite (U-Th-Sm)/He dating results from the Subalpine Molasse, Austria.

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<td>0.69</td>
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<td>29.3</td>
<td>60.5</td>
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eU is the effective uranium concentration, which weights the decay of the parents for their alpha productivity (Flowers et al., 2009); Ft is the α-ejection correction factor, excluded ages have not been taken into account for the geological interpretation because of analytical errors or lack of uranium.
6. Discussion

Uplift and exhumation rates for the external Massif determined from thrust displacement and cooling histories respectively are identical within uncertainty of the data used (see Fig. 1B). Therefore, we assume that exhumation rates are directly proportional to thrust displacement rates and we can estimate the evolution of these rates through time on the base of the reported exhumation data. Displacement of the Aar Massif over its basal detachment is directly related to shortening in the prowedge; shortening is here used as longitudinal strain with respect to the horizontal while thrust displacement – as well as its rates – is measured with respect to slip on the inclined fault surface. Both numbers are only identical for thrust displacement of the rear

and, within the range of uncertainty is thus identical to its present geometry. This is consistent with paleo-elevation studies, which show that the Miocene Alps were probably as high as today (Campani et al., 2012).

Fig. 3. Results of HeFTy modeling for all samples. Dark gray represents good fits and light gray is acceptable fits. Boxes indicate pre depositional time - temperature histories, constraints on depositional time and temperature, and post depositional time - temperature histories, respectively. Note that for sample B25, where both AHe and AFT data is available and also the AFT system witnesses elevated post depositional temperature, an exhumation pulse at ~8 Ma is particularly well constrained.

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end of the proverse and total prowise shortening for a subhorizontal detachment. Fig. 5 shows the individual displacement scenarios for the reported exhumation rates. For the scenario of constant exhumation (Michalski and Soom, 1990; Reinecker et al., 2008; Weisenberger et al., 2012), the corresponding pro-wedge shortening rate ranges between 2.0 and 2.1 mm/a. For the exhumation scenario suggested by Glotzbach et al. (2010), shortening rate is between ~2.6 mm/a from 10 to 7 Ma and thereafter ~1.9 mm/a. Following the proposed scenario of Valla et al. (2012), shortening is as high as 6.8–6.9 mm/a (using their minimum uplift estimates of 2 mm/a) and decreases to ~0.9 mm/a for the time span from 8 Ma to present. In all scenarios shortening rates do not change significantly at least throughout the last ~8 Ma. For the eastern profile, we can analogously calculate shortening rates of 1.8–2.0 mm/a from 10 to 2 Ma and a possible increase thereafter to rates between 2.6 and 2.8 mm/a, which is similar to what we calculated for the western profile (Fig. 5). It is noteworthy that all these scenarios based on thermochronological data imply some active shortening in the Central Alps until present day. This is consistent with results by Champagnac et al. (2009), who calculate the present day shortening rate (based on rotation of the Adriatic plate around an Euler pole located in the Po Basin) to be 1.6 mm/a across the Central Alps in the area of our eastern profile and decreasing rates to ~1 mm/a further west. Note however that part of the post-10 Ma shortening is accommodated in the retro-wedge. Our finding that taper did not change within error of the applied method, and convergence rates are probably comparable since 10 Ma implies that the GPS signal might be dominated by a transient low phase. However, the required shortening rates would be at or below the detection threshold over the noise of GPS analyses (e.g. Calais, 1999; Nocquet, 2012). Additionally, convergence-related rock uplift might be difficult to detect in the Central and Western Alps, because of high glacial overprinting, and consequently high mass wasting rates and isostatic rebound (Hinderer et al., 2013).

We can take the decrease in sedimentation age of the Molasse deposits towards the foreland as proxy for propagation rate of the orogenic front through time. In the eastern profile, the stratigraphic ages show a linear northward decrease between ~21 and 16 Ma over a distance of ~7 km (white boxes in Fig. 2). This yields a propagation rate of ~1.4 mm/a. After 16 Ma, the triangle zone develops and not until 9 Ma the more internal tectonic slices form (see above). Two thirds (i.e. ~20–22 km) of the total shortening occurred after 9 Ma, which means that the orogenic front was stationary in the Subalpine Molasse since that time. This is similar to observations in the western Subalpine Molasse, where stratigraphic ages decrease continuously until 16 Ma and only after 10 Ma, deformation partly jumps into the external Jura Mountains. Yet most of the shortening is accommodated contemporaneously within the Subalpine Molasse as out of sequence reactivation (von Hagke et al., 2012). Since the Alpine front has not propagated beyond the triangle zone – that constitutes the Central Alpine front in the Subalpine Molasse since about 16 Ma – it is also obvious that no material has been advected into the pro-wedge since. As a consequence, the deformation we recorded since the late Miocene is related to internal pro-wedge thickening only. From its constant taper over this time window, we conclude that any thickening-related shape change was balanced by erosion.

Present taper was found to be close to the critical state in the Central Alpine pro-wedge from various present-day kinematic observables (von Hagke et al., 2014). Since taper has not changed, and pro-wedge slip proceeded on the same Alpine basal detachment for the past 10 Ma, the pro-wedge system must have maintained criticality while deforming at a fairly constant rate with erosion keeping pace with internal thickening and relief formation. Together with our finding of constant shortening velocity since 8 Ma, this requires that the pro-wedge has been at steady-state since at least that time frame. This implies that the orogenic wedge and the basal detachment are in dynamic equilibrium since that time, and consequently wedge and detachment strength have probably not changed since 8 Ma.

Our findings have direct implications for the ongoing debate on the potential coupling between climate events and the reported increase in erosion rates worldwide, and in the Molasse basin in particular (Herman et al., 2013; Kuhlemann and Kempf, 2002; Molnar, 2004). Several climate events have impacted the northern Alps, which have may have influenced alpine tectonics (Fig. 6). No correlation between tectonics in the Subalpine Molasse and the Jura Mountains, and climate events is obvious, in particular the tectonic pulses at 10 and 8 Ma are not coincident with climate events. However, the response time of the Alps is estimated to be approximately 5 Myrs (e.g. Roe et al., 2008), which could make the Mid-Miocene Climatic Optimum (Molnar et al., 2005) and the East Antarctic Ice Sheet (Bruch et al., 2007) potential climate changes responsible for the respective tectonic pulses in the Subalpine Molasse. On the other hand, thrusting at that time coincides with onset of folding of the Jura Mountains, which is generally attributed to active convergence and incorporation of a salt detachment into the wedge, rather than climatic forcing (Laubscher, 1961). We therefore conclude that these climatic perturbations did not affect the proverse. After 10 Ma, the situation is less clear, because repeated activity within the Subalpine Molasse partly coincides with reported climate events (Fig. 6). For instance the fast exhumation phase in the foreland basin at approximately 5 Ma was previously related to climatic forcing (e.g.
Cederbom et al., 2004), but may also be a consequence of tectonically induced catchment cannibalization, when the Aare–Danube was captured by the Rhone–Doubs river system at 4.2 Ma (Kuhlemann and Rahn, 2013). The onset of Northern Hemisphere Glaciation at 3.1–2.5 Ma (Haeuselmann et al., 2007; Haug and Tiedemann, 1998) is not witnessed in the thermochronological data, and can therefore not be responsible for major tectonic activity. Maximum glaciation at c. 1.0–0.8 Ma is younger than the youngest reported AHe ages, and therefore cannot explain the data. However, it is noteworthy that the investigated profiles are not in areas of deep glacial scouring. Accordingly, response of the wedge to the most recent glaciation phases might not be covered with our analysis.

Apart from that, we conclude that even though climatic and tectonic events partly coincide, an ultimate link between the two is not supported. This may be explained in different ways. First, as the youngest sediments from the Molasse have been eroded, it is possible that the local climate might have been different from global trends but was dominated by orographic evolution in the nearby area (Mosbrugger et al., 2005). Second, the climatically induced erosion events may be below the detection threshold with the methods used here, i.e. within the range of uncertainty, and may be blurred by a constant background erosion rate. From the above results and arguments it becomes obvious that a constant erosion rate satisfies the results better than one tuned by major climatic events and that none of these climatic events was able to perturb the kinematic equilibrium of the pro-wedge significantly. Interestingly, for the same area Wittmann et al. (2007) report erosion rates based on cosmogenic nuclide analysis that is the same over the postglacial Holocene period as well as over the past 5 Ma. Additionally, von Hagke et al. (2013) show that erosion rate estimates from decadal to million year timescales are similar, when accounting for time-dependent bias of the measurements. This supports the notion of steady state deformation of the Central Alps. Our analysis of the erosion rates of foreland and hinterland exhumation in conjunction with quantitative kinematic analysis of the pro-wedge shows that convergence rather than isostasy sets the pace of exhumation and denudation in the Central Alps.

Finally, constant localization of deformation on the same structures (external Massifs and Subalpine Molasse) within the past 10 Ma beyond the constant taper and slip velocity of the entire pro-wedge requires an understanding of the steady state deformation and erosion of the Central Alps as a consequence of an instantaneous orogeny.

Table 4

A: $\Delta \alpha$ values (i.e. changes in taper angle) based on exhumation values of the Aar Massif, and calculated for different pro-wedge lengths. $\Delta \alpha$ values are highlighted in red. In spite of the calculations with extremely high amounts of eroded section, all values are below 0.5°, indicating that the orogenic taper was stable since 10 Ma. B shows the analogous calculations for the eastern profile. Thrust displacement values used are 20 and 22 km derived from our section balancing. The gray areas are calculated with a décollement dip of 17°, the red areas are calculated with a décollement dip of 21°. $\Delta h$ denotes the difference between measured and restored exhumation.

<table>
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<tr>
<th>Measured exhumation [km]</th>
<th>$\Delta h$</th>
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<th>Distance along profile = 90 km</th>
<th>Distance along profile = 95 km</th>
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<td>0.01</td>
</tr>
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<tr>
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<td>0.41</td>
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<td>4.07</td>
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B: Eastern Molasse basin

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<th>Measured exhumation [km]</th>
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**Fig. 5.** Displacement rates based on exhumation histories. Calculations based on Michalski and Soom (1990), Reinecker et al. (2008) and Weisenberger et al. (2012) (orange), Valla et al. (2012) (blue), Glotzbach et al. (2010) (red) and Hurford et al. (1989) (green). All scenarios show constant displacement rates between ~1 and 3 mm/Ma since ~8 Ma.
Fig. 6. Compilation of tectonic and climatic events affecting the Central Alps: A: thin-skinned Jura thrusting after Källin (1997); B: thick skinned thrusting after Becker (2000) and Madiritsch (2010, 2008). Climate events: (1) Late Oligocene Warming (Mosbrugger et al., 2005), (2) Mid-Miocene Climatic Optimum (Mosbrugger et al., 2005), (3) East Antarctic Ice Sheet (Brücher et al., 2007), (4) Alpine glaciation at 6.26–5.50 (Hodell et al., 2001), (5) Messinian Salinity Crisis at 5.96–5.33 (Hodell et al., 2001; Krijgsman et al., 1999), (6) increased global climate perturbation since 3.8 Ma (Molnar, 2004; Zhang et al., 2013), and gradual increase in moisture supply in Europe due to closure of the Panama Isthmus from 4.6 to 3.2 Ma (Cederbom et al., 2004; Driscoll and Haug, 1998), and (7) Northern Hemisphere Glaciation starting at 3.1–2.5 Ma and reaching its maximum at 1.0–0.8 Ma (Haeuselmann et al., 2007; Haug and Tiedemann, 1998). Erosion in the Molasse Basin after Cederbom et al. (2011, 2004), Williott and Schlunegger (2010), and Kuhlemann and Rahn (2013). Thrusting in the Subalpine Molasse after Trümpy (1980), Cederbom et al. (2011), and von Hagke et al. (2012).

Acknowledgments

Daniel Stöckli and Ray Donelick supported us during AHe and AFT dating. This research was conducted in the framework of the ESF TopoEurope CRP “Thermo–Europe”. The German Research Foundation (DFG) provided funding by research grant number CE 175/1–1. Comments by an anonymous reviewer helped improving an earlier version of this work. We thank Laurent Jolivet for editorial handling.

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7. Conclusions

In this study we presented a new approach for constraining paleo-
taper and mass flux of an orogen by using low temperature thermochronometry combined with wedge dynamics. We show that

- the structures within the Subalpine Molasse were repeatedly active throughout the last 10 Ma, independent of kinematic coupling with the Jura fold-and-thrust belt
- the amount of post-10 Ma shortening within the Subalpine Molasse is similar along the strike of the orogen and at least 17–20 km
- the shortening rates for the northern flank of the Central Alps pro-wedge are constant since at least 8 Ma and fall between 1 and 2 mm/a
- the taper angle of the Central Alps has probably not changed by more than 1° since Late Neogene times
- the Central Alps pro-wedge is, therefore, at steady state since at least 8 Ma
- we have no evidence that individual Miocene to Pliocene climatic events influenced the wedge stability and kinematics on the northern flank of the Central Alps
- constant localization of post-10 Ma deformation on the same structures within the pro-wedge, lack of wedge propagation, and constant taper near criticality suggest a positive feedback between ongoing localized deformation and erosion at low rates.

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