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# 1 Increase in late Neogene denudation of the European Alps 2 confirmed by isoage analysis of a fission-track database

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8

## 9 **Abstract**

10 A sharp increase in deposited sediment volume since Pliocene times has been observed  
11 worldwide and in particular around the European Alps. This phenomenon has been linked to a  
12 rise in denudation rates controlled by an increase of either climatic or tectonic forcing.  
13 Observation of in situ cooling histories for orogens is critical to assess the reality of the  
14 inferred increase in denudation rates, and to determine whether this phenomenon is  
15 widespread or localized at active tectonic structures. We exploit the unique density of fission  
16 track ages in the Western European Alps to reconstruct cooling isoage surfaces and to  
17 estimate exhumation rates on the orogen scale between 13.5 and 2.5 Ma. Our novel technique  
18 is based on the association of isoage contours with age-elevation relationships. It uses map-  
19 view interpolation, enabling a spatio-temporal analysis of exhumation rates over the entire  
20 Western Alps. The resulting exhumation histories reconstructed for eight areas of the Western  
21 Alps display strong similarities in timing and rates with orogen-wide average denudation rates  
22 inferred from sediment volumes. This consistency validates the use of both techniques for the  
23 study of an orogen characterized by strong relief and high recent exhumation rates. We  
24 conclude that exhumation rates in the Western Alps have increased more than twofold since

25 late Miocene times. This increase may have been locally modulated by the distinct response  
26 of different tectonic units.

27

28 Keywords: Cenozoic exhumation, Fission track, Isoage surfaces, Western Alps

29

## 30 **1. Introduction**

31 Widespread indications for an increase of global sedimentation rates in the early Pliocene  
32 have been reported from localities around the world (e.g., Molnar, 2004; Zhang et al., 2001).  
33 However, the cause of this event, its exact timing and synchronicity remain controversial.  
34 Possible causes that have been proposed include global cooling and incipient glaciations  
35 (Ehlers et al., 2006; Hinderer, 2001), an increase in the magnitude and frequency of climate  
36 oscillations (Molnar, 2004; Zhang et al., 2001), and a recent increase in the uplift rates of  
37 major orogens (Raymo and Ruddiman, 1992).

38

39 The quantification of sediment volumes in the basins surrounding the European Alps by  
40 Kuhlemann et al. (2002) shows a more than twofold increase in erosion rates in both the  
41 Western and Eastern Alps around 5 Ma (Figure 1). An independent study of the exhumation  
42 of the Molasse basin (Figure 2), based on borehole apatite fission-track data, demonstrated  
43 approximately 1400 m of basin exhumation since 5 Ma, interpreted as a record of isostatic  
44 rebound of the basin driven by accelerated erosional unloading of the Alps (Cederbom et al.,  
45 2004).

46

47 The estimation of source-area denudation rates from the sediment record suffers, however,  
48 from poorly quantified uncertainties in both the volumetric calculations and the dating  
49 accuracy (Kuhlemann et al., 2002). Moreover, the impossibility of quantifying the roles of

50 chemical erosion and sediment recycling may lead to an underestimation or overestimation,  
51 respectively, of source-area denudation rates.

52

53 An increase in exhumation at ca. 5 Ma, if real, should be recorded more directly by low-  
54 temperature thermochronometers in the bedrock of the mountain belt. Classically, the  
55 derivation of exhumation rates from thermochronometry is based on temperature-time paths  
56 reconstructed from multiple thermochronometer analysis, age-elevation profiles from  
57 altitudinal transects or boreholes, or kinetic modeling of apatite fission-track annealing using  
58 track-length distributions (e.g., Gallagher et al., 1998; Hurford, 1991). In different regions of  
59 the Western Alps, Neogene-age exhumation rates quantified using these approaches range  
60 between 0.1 and 1.5 mm/yr (e.g., Leloup et al., 2005; Malusa et al., 2005; Michalski and  
61 Soom, 1990; Tricart et al., 2007). However, most of these studies are local or at best regional  
62 in scope and a consistent denudation history at the orogen scale has yet to emerge. Apatite  
63 fission-track (AFT) thermochronology appears the most suitable technique to study Mio-  
64 Pliocene exhumation rates over a large area such as the Western Alps because of the  
65 abundance of ages ready for database compilation, and because the AFT age range (Figure 3-  
66 a) comprises the target period of the late Neogene.

67

68 The spatial integration of discrete thermochronological data covering large study areas is most  
69 easily achieved by interpolating between ages in map view (e.g., Hunziker et al., 1992;  
70 Figures 3-a and 3-b). However, this simple technique only presents the integrated result of a  
71 possibly complex denudation history and does not allow variations in denudation rate through  
72 time to be inferred. Published methods aimed at describing the history of exhumation rates in  
73 map view have used either analysis of multiple thermochronometers, or kinetic modeling of  
74 fission-track length distributions (e.g., Bistacchi and Massironi, 2000; Gallagher and Brown,

75 1999; Morris et al., 1998; Schlunegger and Willet, 1999; Stephenson et al., 2006). Despite  
76 many years of intensive thermochronological studies in the Alps, samples permitting such  
77 analyses are still relatively rare, disallowing such a study at the orogen scale. Techniques  
78 based on modeling of fission-track length distributions offer the greatest wealth of  
79 interpretation in settings characterized by slow long-term denudation, such as rifted  
80 continental margins (e.g. Gallagher and Brown, 1999). In rapidly exhuming orogens, in  
81 contrast, track-length distributions are not easily measured (because of generally young AFT  
82 ages) and are much less discriminative.

83  
84 We propose a new method in which we exploit the extensive AFT dataset available for the  
85 Western Alps (Figures 2 and 3) together with the significant relief of the mountain belt to  
86 reconstruct three-dimensional surfaces of equal AFT age (referred to here as isoage surfaces).  
87 We subsequently use the difference in elevation between these surfaces to estimate the spatial  
88 pattern in rates of exhumation back to middle Miocene times (13.5 Ma), as recorded in the  
89 spatial relationship between AFT ages at outcrop today. The aims of this study are to test for  
90 the presence of changing exhumation rates during late Neogene times across the Western  
91 Alps, and if present, to describe the temporal and spatial variability of this signal. In addition,  
92 we present updated maps of interpolated apatite fission-track ages and mean track lengths, as  
93 well as zircon fission-track ages. We complete this study by the assessment of evolving trends  
94 of exhumation rates using samples with paired zircon and apatite fission-track ages. In the  
95 following, we first briefly outline the geological setting and evolution of the Alps and present  
96 the thermochronological database we constructed. We then explain the different methods we  
97 used to analyze the database. Finally, we present our main results and their implications for  
98 the late Neogene denudation history of the Alps as well as its possible tectonic or climatic  
99 controls.

100

## 101 **2. Geological setting of the Alps**

102 The European Alps (Figure 2) are located at the boundary between the European and Apulian  
103 plates. They are the product of the early Cretaceous closure of the Piemont-Ligurian ocean,  
104 followed by continental subduction resulting in nappe stacking (cf. reviews in Rosenbaum  
105 and Lister, 2005; Schmid et al., 2004).

106

107 The main tectonic units in the Alps and their structural relationships have been described  
108 extensively within the last century (e.g., Debelmas and Lemoine, 1970; Schmid et al., 2004;  
109 Trümpy, 1960). They originate from the European continental margin basement (External  
110 Crystalline Massifs) and overlying deposits (Helvetic sediments), the Briançonnais micro-  
111 continent and its two bordering oceanic units (Piemont-Ligure and Valais oceanic crust and  
112 flysh), and finally basement and sedimentary units of the Apulian margin, grouped as the  
113 Austroalpine and the South Alpine units (Figure 2). The North (Molasse) and South (Po)  
114 Alpine foreland basins formed by flexure of the lithosphere in response to the weight of the  
115 orogenic prism on the European and Apulian plates and are filled with Eocene to Recent  
116 flysch, molasse and glacial deposits (e.g., Homewood et al., 1986; Scardia et al., 2006).

117

118 One of the most important arc-parallel tectonic boundaries, the Penninic thrust, may have  
119 been extensionally reactivated (Seward and Mancktelow, 1994) as part of a series of Neogene  
120 extensional features observed throughout the axial region of the Western Alps (e.g., Sue et al.,  
121 2007; Tricart et al., 2007 and references therein). Most of these extensional features may be  
122 caused by a Neogene dextral transtensive event (Sue et al., 2007) triggered by the anti-  
123 clockwise rotation of the Apulian plate. Such rotation can also explain the current strain  
124 pattern in the Western Alps (Calais et al., 2002). At present, geodetic and GPS data show

125 limited ( $\leq 2$  mm/yr) east-west extension in the Western Alps (Calais et al, 2002; Sue et al.,  
126 2007). The lack of present-day convergence in the Western Alps, together with the  
127 observation of sediment-sealed thrusts in the western part of the Po basin (Pieri and Groppi,  
128 1981), and the cessation of thin-skinned deformation in the Jura at ca. 4 Ma (Becker, 2000) all  
129 suggest very limited current orogenic activity within the chain.

130

131 We limit our study area to the Western half of the Alps, as far east as the Silvretta nappe /  
132 Engadine window, or approximately the Swiss-Austrian border, which marks the western  
133 limit of widespread outcrop of Austroalpine units. The reason for this eastern limit to the  
134 study area is that few AFT studies have been published for the Austroalpine units because of  
135 the low abundance of apatite in their constitutive lithologies.

136

### 137 **3. Data**

#### 138 **3.1. Apatite and zircon fission-track databases**

139 During the last thirty-five years, the Western Alps have been extensively sampled for  
140 thermochronological analyses, in particular using the apatite and zircon fission-track  
141 thermochronometers, characterized by closure temperatures of ca. 120 and 240 °C  
142 respectively (e.g., Brandon et al., 1998; Gallagher et al., 1998). We have compiled 740 AFT  
143 ages, from data in 37 publications completed by 160 unpublished ages (references are given in  
144 the caption of Figure 3-a) from samples located in the European Alps west of 10° 20' east (an  
145 area of ca. 48000 km<sup>2</sup>). We similarly compiled 380 zircon fission-track (ZFT) ages from 24  
146 publications completed by 22 unpublished ages (see Figure 3-b for references).

147

148 **3.2. Quality and homogeneity of the data**

149 Early studies (in the 1970's and early 1980's, see for instance Wagner and Reimer, 1972)  
150 used the population method for AFT dating, whereas the more reliable external detector  
151 method (Hurford and Green, 1982) has become the norm since the mid 1980's. The database  
152 contains ages obtained both with the population and the external-detector dating techniques  
153 because we feel that, at the regional scale of the study, the benefits of increasing data density  
154 outweigh the drawbacks of the error introduced by less reliable data points. We rejected three  
155 samples with an obvious mistake in dating, in cases where a ZFT age was younger than or  
156 equal to (within error) the AFT age of the same sample.

157  
158 Additional information collected for each sample included (where reported): (1) geographic  
159 coordinates, (2) elevation, (3) mean track length for AFT samples, (4) whether the sample is  
160 from a tunnel / borehole or the surface, and (5) whether fission-track ages of samples from  
161 Mesozoic and Cenozoic sediments are younger than their stratigraphic age (that is, whether  
162 they have been reset during Alpine orogeny). To apply the latter criterion, we assumed that  
163 ages from sedimentary samples were non-reset unless we could estimate the depositional age  
164 and verify that it was older than the fission-track age. A few publications contained more than  
165 one age at a given geographic location (referred to later as points with non-unique ages). We  
166 discarded such points from part of the study, in order to prevent problems with map  
167 interpolation. Many of the original publications did not report sample elevations and / or  
168 coordinates. We obtained this missing information by interviewing the authors whenever  
169 possible, or alternatively by reading it off topographic maps or figures from the original  
170 publications. As a last resort, we estimated the elevation of samples from the Digital  
171 Elevation Model (DEM), which consists of a mosaic of the 38-03, 38-04, 39-03 and 39-04  
172 DEM tiles available from the CGIAR-CSI SRTM 90 m database (<http://srtm.csi.cgiar.org>).



173 All numerical data fields in the database (coordinates, altitude, age, etc.) carry a degree of  
174 uncertainty that varies between publications. For instance, the relative standard errors  
175 affecting the AFT and ZFT ages used in this paper vary between 2.2 and 51.6 % (average:  
176 11.6 %) for the former, and between 0.7 and 23.3 % (average 8.0 %) for the latter.

177

## 178 **4. Methods**

179 We have developed three joint approaches to take advantage of the high spatial density of  
180 fission-track ages in the Western Alps. First, we interpolated AFT and ZFT ages (Figures 3-a  
181 and 3-b); second, we calculated cooling and exhumation rates using samples dated with both  
182 methods; and third, we constructed isoage surfaces. The latter were used to infer histories of  
183 exhumation rates for different areas of the Western Alps between 13.5 and 2.5 Ma.

184

### 185 **4.1. Maps of interpolated ages / track lengths**

186 Using the natural-neighbor interpolation tool provided by the ESRI-ArcMap9<sup>tm</sup> GIS, we  
187 created two maps of 635 AFT ages and 296 ZFT ages covering the Western Alps (Figures 3-a  
188 and 3-b). For this interpolation, we selected points from the database following three criteria:  
189 (1) ages in sedimentary rocks should be reset; (2) samples should be from the surface; and (3)  
190 points with non-unique ages are discarded. No potentially arbitrary constraints such as  
191 tectonic boundaries or elevation corrections were used in this initial interpolation. The choice  
192 of a natural-neighbor interpolator is justified by its conservative properties, resulting in  
193 finding at each pixel of the map a weighted average of the neighborhood data points without  
194 introducing artefacts (Watson, 1999). However, as we could not introduce a maximum  
195 distance of interpolation, localities within the inner Alpine arc are often interpolated between  
196 data points located very far apart, at two extremities of the arc. Figure 3-c shows a map of 258  
197 mean AFT lengths, interpolated in the same manner as the ages.

198

#### 199 **4.2. Exhumation rates calculated from paired ZFT and AFT ages**

200 We extracted from the database a subset of 143 samples with paired AFT and ZFT ages,  
201 following the requirements that (1) they are surface samples; (2) both AFT and ZFT ages are  
202 younger than 35 Ma (i.e., Alpine cooling ages); (3) AFT and ZFT ages differ by at least 1.6  
203 Myr (an empirical limit set by convergence problems for smaller age differences in the  
204 numerical code used); finally (4) points with non-unique ages are discarded. The 143 age  
205 pairs offer the opportunity to estimate two successive average exhumation rates: an initial rate  
206 during the time between closure of the ZFT and AFT thermochronometers, and a final rate for  
207 the time since closure of the AFT system. We used a modified version of the one-dimensional  
208 model of Brandon et al. (1998) to calculate iteratively the depth of closure of the ZFT and  
209 AFT systems, and then calculate exhumation rate from the value of closure depth and age.  
210 This model takes into account the advective perturbation of a steady-state geotherm by  
211 exhumation, as well as the dependence of closure temperature on cooling rate (e.g., Dodson  
212 1973). It does not, however, include 2-D or 3-D effects such as non-vertical rock-particle  
213 paths, spatial variation in geothermal gradient or topographic effects. We have adapted the  
214 Brandon et al. (1998) model to simultaneously estimate closure temperatures and depths for  
215 both the ZFT and AFT systems (cf. Braun et al., 2006 and van der Beek et al., 2006 for  
216 details), using values for the kinetic parameters as estimated by Brandon et al. (1998): AFT:  
217  $E_a = 186.4 \text{ kJ mol}^{-1}$ ,  $D_0/a^2 = 3.64 \times 10^{10} \text{ s}^{-1}$ ; ZFT:  $E_a = 208.2 \text{ kJ mol}^{-1}$ ,  $D_0/a^2 = 3.70 \times 10^6 \text{ s}^{-1}$ .  
218 Other parameter values used in the model are: surface temperature  $T_s = 15 - (6 \times \text{elevation}$   
219  $(\text{km})) \text{ }^\circ\text{C}$ , initial (non-perturbed) geothermal gradient  $G = 25 \text{ }^\circ\text{C km}^{-1}$ , model thickness  $L = 25$   
220  $\text{km}$ , thermal diffusivity  $\kappa = 25 \text{ km}^2 \text{ Myr}^{-1}$ . The model predicts initial and final exhumation  
221 rates that are consistent with both ages; the ratio between the final and initial rates indicates  
222 whether the average exhumation rate accelerated or decelerated after closure of the AFT

223 system. An interpolated map of this ratio is plotted in Figure 4. Absolute values of predicted  
224 exhumation rates are affected by the assumed initial geothermal gradient, which is largely  
225 unknown and may vary spatially. However, the *ratio* between final and initial rates is not  
226 sensitive to this parameter, providing the geothermal gradient does not change through time,  
227 other than through advective perturbation.

228

### 229 **4.3. Reconstruction of isoage surfaces**

230 Apatite fission-track isoage surfaces join all rocks predicted to have cooled through the AFT  
231 closure temperature at the same time (Figure 5). They are obtained by interpolation in map  
232 view between the elevations of points having the same AFT age. Providing the assumption  
233 that the depth of the AFT closure isotherms is only moderately affected by changes in  
234 exhumation rate, the latter can be estimated using the vertical distance between two  
235 successive isoage surfaces. In this respect, isoage surfaces may be viewed as a 3-D  
236 generalization of the 1-D age-elevation profile concept, allowing the same information on  
237 denudation history to be extracted on a regional scale and potentially recording spatial  
238 variations in denudation rates through time.

239

240 Regional variability in geothermal gradient, cooling history and / or apatite annealing kinetics  
241 may cause the closure temperature and depth to vary spatially between samples from different  
242 tectonic units, thus potentially imposing secondary effects on the spatial variation in elevation  
243 of isoage surfaces. However, as for age-elevation profiles, the denudation rate inferred from  
244 the elevation difference between successive isoage surfaces is independent of the absolute  
245 closure temperature and depth, as long as these remain constant through time. Temporal  
246 variations in exhumation rates may affect the AFT closure temperature (Dodson, 1973) as  
247 well as the geometry of near-surface isotherms (e.g., Braun, 2002; Stüwe et al., 1994). These

248 two factors tend respectively toward over- or under-estimation of the exhumation rate in the  
249 case of an increase in exhumation rate. Nevertheless, the characteristic diffusive timescales  
250 are rather large (e.g., Braun et al., 2006) so that these variations will be relatively small over  
251 the 1 Myr time span separating two isoage surfaces. In any case, the latter effect significantly  
252 outweighs the former (e.g., Braun et al., 2006), so that estimated exhumation rates during a  
253 period of increase before reaching a thermal steady-state are likely to be minimum estimates.

254

#### 255 **4.3.1. Production of arrays of isoage points**

256 The most obvious way to obtain x, y, z coordinates of isoage points is to use the elevation of  
257 isoage contours, which, by definition, are the lines of intersection between isoage surfaces and  
258 the Earth's surface. We extracted the elevation of each isoage contour traced on the maps of  
259 interpolated AFT ages (Figure 3-a) by projection on the Digital Elevation Model (DEM). The  
260 spatial resolution of the DEM (90 m) is much higher than the resolution of the isoage contours  
261 (controlled by interpolated points often separated by several kilometers). Therefore, the  
262 elevation of any segment of an isoage contour has a high pixel-to-pixel variability (or noise)  
263 due to the short-wavelength topography sampled. Nevertheless, the average local value should  
264 accurately reflect the elevation of the intersection between an isoage surface and the  
265 topography.

266

267 We added a second series of isoage points to the array, based on local estimates of AFT age-  
268 elevation relationships (AER) in the neighborhood of data points where the correlation  
269 between these two parameters was statistically significant (Figure 6). The aim is to document  
270 areas where the AER are well correlated and use them to interpolate the elevation of isoage  
271 surfaces. We used a subset of 660 AFT samples with an age younger than 35 Ma for this  
272 approach. Sample elevation values that had to be derived from the DEM were found to

273 introduce too much noise in the calculation of regression coefficients for age-elevation  
274 relationships and were therefore rejected. We did include, however, data points with non-  
275 unique ages, as they comply with the requirements to estimate age-elevation relationships.  
276 The condition of sample ages younger than 35 Ma aims to avoid introducing samples that are  
277 manifestly partially reset, such as those with Mesozoic ages from the Southern Alps (cf.  
278 Figure 3-a), into the calculation of AER regression lines.  
279  
280 For our semi-automated AER analysis, we first selected the neighbors of every point in the  
281 database, included in a circle of increasing radius (from 3 to 15 km). For every selection  
282 containing more than 4 points, we calculated a regression line between age (dependent  
283 variable) and elevation (independent variable), together with its correlation coefficient. The  
284 AER was judged significant and was retained if the correlation coefficient for the regression  
285 was higher than the critical Pearson's product-moment coefficient at 95 % confidence level  
286 for the appropriate number of degrees of freedom (cf. Figures 6-b and 6-c). When the initial  
287 selection around a data point (3 km radius) failed this statistical test, we incrementally  
288 increased the search radius by 2 km steps to a maximum of 15 km. This maximum presents a  
289 characteristic distance between adjacent valleys: for larger search radii, the samples selected  
290 may belong to adjacent valleys with distinct exhumation histories. We used the regression  
291 equations calculated from the set of points selected within the smallest successful search  
292 radius possible, because they constitute the closest equivalent to a vertical profile and  
293 therefore carry the smallest risk for the AER to be affected by either large-scale tilting (Rahn  
294 et al., 1997) or the deflection of isotherms in large Alpine valleys (e.g., Braun, 2002; Stüwe et  
295 al., 1994).  
296

297 The local AER is described by the simple linear equation  $z = A_0 + (A_1 \times t)$ , where  $A_0$  is the  
298 elevation of the zero-age intercept, and  $A_1$  is the slope of the AER (with  $z$ : elevation [m];  $t$ :  
299 age [Ma]). Statistically significant AERs extracted from the data are used to interpolate the  
300 elevations of isoage surfaces at the location of the center of the search radius, limiting the  
301 extrapolation to between 1 Myr before the oldest and 1 Myr after the youngest age in the  
302 neighborhood selection. This limitation is imposed in order to avoid extrapolating age-  
303 elevation trends into periods during which they are not locally documented. In case of a  
304 slightly kinked AER (i.e. change in exhumation rate with time), the slope  $A_1$  would be  
305 averaged; if the kink is more pronounced the linear correlation coefficient will be insignificant  
306 and the neighborhood selection rejected. Given that this study is aimed at testing for changing  
307 exhumation rates through time, the rejection of kinked AERs in the generation of isoage data  
308 points is conservative, and will downplay any signal.

309

#### 310 **4.3.2. Interpolation of isoage point arrays**

311 We constructed isoage surfaces by natural-neighbor interpolation applied to the elevations of  
312 the points constituting each isoage array (Figure 6d). In order to remove unconstrained parts  
313 of the surfaces, which have been interpolated far from any point of the isoage arrays, a mask  
314 is applied at 15 km around the point arrays. The oldest isoage surfaces have been eroded from  
315 large parts of the study area, while the youngest surfaces remain buried in other areas,  
316 resulting in a heterogeneous scatter of each array of isoage points. The result is a series of  
317 thirteen maps showing isoage surfaces between 14 and 2 Ma where they can be reconstructed  
318 with reasonable accuracy; a representative selection of six isoage surfaces is reported in  
319 Figure 7.

320

321 **4.4. Estimation of exhumation rates**

322 The vertical distance between two isoage surfaces corresponds, in principle, to the amount of  
323 exhumation during the time period separating them, with the same caveats that apply to the  
324 interpretation of 1-D age-elevation profiles, notably the effect of topography on the AER  
325 slope (Braun, 2002). In the crystalline massifs of the Western Alps, geomorphic data suggest  
326 a significant recent increase in relief (e.g., Champagnac et al., 2007; van der Beek and  
327 Bourbon, 2008) so that we expect topographic effects to be limited and the distance between  
328 successive isoage surfaces to provide a reliable estimate of exhumation.

329  
330 After being clipped by the 15 km mask, each isoage surface covers only a limited portion of  
331 the Western Alps, and two successive surfaces are never completely superposed. Therefore, it  
332 is not possible to calculate the total volume exhumed over the entire surface of the Western  
333 Alps during any time period. Instead, we focused on eight specific areas characterized by  
334 several million years of continuous isoage surface coverage (Figure 8).

335  
336 The difference in elevation between successive isoage surfaces is calculated for all 1.2 km<sup>2</sup>  
337 pixels of each study area and the average distance constitutes our estimate of exhumation  
338 during the corresponding time period. Some pixels show negative differences, i.e. the younger  
339 isoage surface lies above the older one. These correspond either to artefacts introduced by our  
340 treatment of the data or to local areas of strong recent relief decrease. We decided to exclude  
341 these pixels from our calculation of the average distance between isoage surfaces, as two  
342 isoage surfaces cannot cross each other in an exhuming massif. To illustrate pixel value  
343 distributions, Figure 9 presents the values measured between the surfaces aged 5 and 4 Ma for  
344 the Mont Blanc area. Plotted against time, the average distances between isoage surfaces  
345 enable quantifying the temporal evolution of exhumation rates over each area (Figure 10).

346

347 Samples that underwent slow cooling through the partial annealing zone may lead to apparent  
348 AERs that do not correspond to the exhumation rate (e.g., Gallagher et al., 1998). The mean  
349 track lengths can be used to monitor whether this is the case, as samples that cooled slowly  
350 through the partial annealing zone are characterized by mean track length  $\leq \sim 12.5 \mu\text{m}$ . Most  
351 areas covered by our constructed isoge surfaces are characterized, in contrast, by sample  
352 mean track length  $\geq 13 \mu\text{m}$  (compare Figures 3-c and 8), with the exception of the Bergell and  
353 the Aar-Leventina (areas 1 and 6 in Figure 8).

354

## 355 **5. Results**

### 356 **5.1. Main features of the fission-track age patterns**

357 Young AFT ages ( $< 10 \text{ Ma}$ ) appear in the axial region of the Western Alps (Figure 3-a) and  
358 particularly over the Argentera, Ecrins - Mont-Blanc, and Aar External Crystalline Massifs.  
359 Very young ages ( $< 5 \text{ Ma}$ ) are also found in the Chur region, between the eastern Aar and the  
360 Silvretta nappe, and in the western Lepontine dome, east of the Simplon fault. In contrast, the  
361 internal crystalline massifs (Gran Paradiso, Dora Maira) as well as the Austroalpine units are  
362 characterized by early Miocene or older AFT ages ( $> 10 \text{ Ma}$ ). An inverse relationship  
363 between AFT age and mean track length appears, with ages  $< 10 \text{ Ma}$  generally characterized  
364 by mean track length  $> 13 \mu\text{m}$  (compare Figures 3-a and 3-c). The only exception to this  
365 pattern is a band of short mean track lengths extending from the central Aar massif to the SSE  
366 (Figure 3-c). Young ZFT ages ( $< 15 \text{ Ma}$ ) characterize the Aar, Mont-Blanc, Belledonne and  
367 Lepontine massifs (Figure 3-b). Extensive regions of both the external and internal parts of  
368 the orogen show early Alpine ZFT ages (20-35 Ma), whereas two orogen-parallel bands (an  
369 external band covering the frontal parts of the Mont-Blanc and Aar massifs and an internal



370 band running from the eastern Ecrins across the Southern Alps) show ZFT ages that were not  
371 reset by the Alpine orogeny (i.e., ZFT age  $\geq$  35 Ma).

372

373 The AFT and ZFT age patterns run parallel to two major Alpine tectonic lineaments: the  
374 Penninic thrust, bordering the External Crystalline Massifs, and the Simplon fault. Both areas  
375 show younger ages in their footwalls (Figures 3-a and 3-b), which suggests that a component  
376 of tectonic exhumation may affect the age patterns, as previously suggested in more local  
377 studies (Fügenschuh and Schmid, 2003; Seward and Mancktelow, 1994; Tricart et al., 2007).

378

### 379 **5.2. Variation in exhumation rate from paired AFT and ZFT ages**

380 A pattern of recent accelerated exhumation, dominantly affecting the external side of the belt  
381 (and the External Crystalline Massifs in particular), is evidenced in Figure 4. This map  
382 demonstrates an overall acceleration in exhumation rate along the northern and western  
383 borders of the orogen, since these areas crossed the AFT closure temperature of  $\sim$ 120 °C.

384 AFT ages in the region showing accelerated denudation are mostly  $\leq$  8 Ma (compare Figures  
385 3-a and 4). However, exhumation rates used in this ratio calculation are average values for  
386 initial cooling between the ZFT and AFT closure temperatures and final cooling between the  
387 AFT closure temperature and the surface, and do not enable us to resolve when the  
388 acceleration occurred.

389

### 390 **5.3. Description of isoage surfaces**

391 The elevation of isoage surfaces generally increases with age (see legend on each map of  
392 Figure 7), which is consistent with the assumption that isoage surfaces are mainly controlled  
393 by the effect of denudation on isotherms (Figure 5). The overall shape of the isoage surfaces  
394 is that of arcuate domes, the axes of which are roughly superposed with the External

395 Crystalline Massifs (Aar, Mont-Blanc and Ecrins, see Figure 2) for the younger surfaces, and  
396 with more internal massifs (Lepontine Alps, Dent-Blanche) for older surfaces. Young isoage  
397 surfaces are defined mostly by points from high-relief areas with young fission-track ages in  
398 the valleys, whereas old isoage surfaces are controlled by locally old fission-track ages  
399 encountered on topographic peaks and the elevation of isoage contours in the periphery of the  
400 orogen.

401

#### 402 **5.4. Spatial and temporal evolution of exhumation rates**

403 The difference in elevation of AFT isoage surfaces was used to estimate exhumation rates  
404 between 13.5 and 2.5 Ma over the Western Alps (Figures 7-10). Comparing curves of  
405 exhumation rate against time for different sub-areas (Figure 10) highlights a series of eight  
406 overlapping segments from 9.5 to 2.5, 9.5 to 4.5, 13.5 to 10.5 and 13.5 to 4.5 Ma, which all  
407 share a similar trend. The estimates of exhumation rate vary between 200 and 700 m/Myr,  
408 with an acceleration centered around 5 Ma, which is in surprisingly good agreement with peri-  
409 alpine sedimentation rates and inferred alpine denudation rates reported by Kuhlemann and  
410 co-workers (Kuhlemann, 2000; Kuhlemann et al., 2002). While we are mostly interested in  
411 the pattern of denudation rates at the orogen scale, regional variations in the exhumation  
412 history demonstrate the localization of denudation (Figure 10). The exhumation rates  
413 estimated in the Bergell and Valais-Sesia areas (curves 1 and 2) are similar and indicate a  
414 denudation rate of ~300 m/Myr between 13.5 and 10.5 Ma. The Ecrins and Mont-Blanc  
415 massifs (curves 3 and 4) share a similar pattern of increase in exhumation rate between 5.5  
416 and 4.5 Ma, with recent rates reaching 500 m/Myr. Further east, the Aar-Leventina area  
417 (curve 6) shows a slightly earlier increase in exhumation rate (~6 Ma). However, the  
418 occurrence of short mean track lengths in the Aar-Leventina and the Bergell areas (cf. section  
419 4.4) may lead us to overestimate recent exhumation. In contrast, the onset of the acceleration

420 in the Simplon and Chur areas (curves 5 and 7) appears to be younger than 3.5 Ma, with  
421 recent denudation rates reaching over 600 m/Myr. The sub-area with the longest continuous  
422 coverage in isoage surfaces (area 8 on Figure 8) combines a suite of small areas in the  
423 Western Alps. The values of exhumation rate it provides between 13.5 and 4.5 Ma (curve 8 on  
424 Figure 10) are included within the range of the seven other sub-areas.

425

## 426 **6. Discussion**

### 427 **6.1. Conditions of use of isoage surfaces**

428 The use of isoage surfaces to calculate exhumation rates through time requires that the  
429 surfaces have not been significantly deformed. Therefore, actively deforming thrust belts  
430 would need to be treated with caution. Locations undergoing relief reduction are also to be  
431 avoided because age-elevation relationships would provide overestimates of exhumation rates  
432 (Braun, 2002). The optimal conditions are met in orogens where relief is either steady or  
433 increasing, and tectonic activity is insufficient to significantly deform the isoage surfaces. The  
434 Western Alps are a successful candidate because relief appears to have increased recently due  
435 to glaciations (Champagnac et al., 2007; van der Beek and Bourbon, 2008), whereas present-  
436 day tectonic activity is limited (e.g., Calais et al., 2002). Moreover, the European Alps are  
437 covered by an exceptional density of existing AFT ages, allowing us to use the approach  
438 developed here.

439

### 440 **6.2. Errors affecting exhumation rate calculations**

441 Several types of error potentially affect the calculation of exhumation rates from isoage  
442 surfaces: (1) uncertainties affecting the ages, elevations and coordinates of samples in the  
443 database used to compute isoage surfaces, (2) heterogeneous scatter of the interpolated data  
444 points, and (3) geological factors such as the composition of apatites (defining their precise

445 closure temperature) and spatial or temporal variations in relief and geothermal gradient.  
446 While errors of type 1 can be estimated on a sample per sample basis, propagating these into  
447 an uncertainty in isoage surface elevation cannot be done rigorously, although a Monte Carlo  
448 approach in which the surfaces are created thousands of times while varying the input data  
449 within error could be envisaged. Whereas uncertainties of type 2 (role of sampling density and  
450 scatter) are generally assessed using kriging techniques, these are limited for geological  
451 applications because of strong assumptions on spatial continuity and statistics of the data.  
452 Alternatively such errors may be evaluated using calculation-intensive boot-strap techniques.  
453 Uncertainties of type 3, however, are practically impossible to quantify. Moreover, the weight  
454 of these three types of errors within the final uncertainty in exhumation rates is unknown.  
455 Therefore, we chose to present the estimates of exhumation rates as such, without the addition  
456 of an inherently partial and, therefore, misleading error.

457

### 458 **6.3. Comparison between exhumation rates and the volume of sediment deposited** 459 **through time**

460 The exhumation rates calculated from the AFT isoage surfaces over the Western Alps (Figure  
461 10) are of the same order (200-600 m/Myr) as those calculated from the sedimentary record  
462 (Kuhlemann, 2000; Willett et al., 2006). They are also, more expectedly, comparable with  
463 denudation rates obtained from local thermochronological studies (e.g., Michalski and Soom,  
464 1990; Schär et al., 1975; Schlunegger and Willett, 1999; Tricart et al., 2007). Thus, both the  
465 sedimentary record and the in-situ thermochronological record show a similar increase in  
466 exhumation rates around 5 Ma. However, the thermochronometric estimates of denudation  
467 rates are overall slightly higher than those obtained from the sedimentary record (Figure 10).  
468 This small offset may be explained by the fact that areas with the most complete isoage  
469 surface coverage, which are used in the calculations, are biased toward the more rapidly

470 eroding massifs with young AFT ages in the valleys, and therefore do not constitute a  
471 representative sampling of the entire Western Alps. Other explanations could be an  
472 overestimation of exhumation rates obtained from age-elevation relationships (Braun, 2002)  
473 or a general bias in the calculation of sediment volume, which, for instance, does not take  
474 chemical weathering or sediment recycling into account.

475

#### 476 **6.4. Possible causes for increased recent exhumation**

477 Over the last 14 Myr, the shift of the apex of isoage surface domes through time from the  
478 inner Alps to the External Crystalline Massifs (Figure 7) suggests a shift of the most actively  
479 exhuming regions during late Miocene and Pliocene times. This idea is in agreement with the  
480 map of the ratio of final / initial exhumation rates (Figure 4), where acceleration of  
481 exhumation is observed after AFT closure in the External Crystalline Massifs..

482

483 Within this general frame, we observe a broad increase in exhumation rate in the Western  
484 Alps centered around 5 Ma, with local variations in the timing of this increase (Figure 10).  
485 Assuming that these variations are significant compared to the unquantified uncertainty, they  
486 suggest that the rise in Alpine denudation described as happening around 5 Ma (e.g.  
487 Cederbom et al., 2004; Kuhlemann, 2000), actually varied considerably, taking place between  
488 6.5 and 2.5 Ma depending on local tectonic and structural conditions. A clear expression of  
489 regional diversity within a general trend of exhumation increase is found in the Simplon and  
490 Chur areas (Figures 8 and Figure 10). The recent surge in exhumation rates in these areas can  
491 be linked spatially to present-day high rock-uplift rates in the western and eastern Aar massif  
492 (e.g., Persaud and Pfiffner, 2004). Although a significant part of present-day rock uplift rates  
493 could be due to the isostatic response to erosional unloading (Champagnac et al., 2007;  
494 Schlunegger and Hinderer, 2001), this spatial link may suggest that these two locations are

495 characterized by high rock uplift rates since at least the time of AFT closure. Furthermore,  
496 this pattern suggests that current exhumation of the Aar massif is concentrated on its western  
497 and eastern borders, and has been so for several million years.

498

499 Based on the approximate temporal coincidence between Mio-Pliocene acceleration of  
500 exhumation in the Western Alps, and the closure of the Panama isthmus and subsequent  
501 reorganization of Atlantic Ocean currents, Cederbom et al. (2004) proposed that the increase  
502 in exhumation around 5 Ma was externally controlled by increased precipitation over Europe.

503 An alternative, and more global mechanism, is that the increased variability of climate  
504 witnessed by the ocean oxygen isotope record forced accelerated erosion rates, although the  
505 data suggest that this happened between 4 and 3 Ma (e.g., Molnar, 2004; Zhang et al., 2001).

506 Although this explanation remains difficult to confirm, it is seducing as a cause on a global, or  
507 at least a continental, scale could explain the simultaneous increase in exhumation in other  
508 orogens (e.g., Molnar, 2004; Zhang et al., 2001). Uplift of the Western Alps followed by  
509 widespread exhumation may also be controlled by a deep-seated event such as slab  
510 detachment; however, no evidence exists to tie such an event down at this particular time.

511

## 512 **7. Conclusions**

513 Our analysis of the complete fission-track thermochronology database in the Western Alps  
514 leads to the following general conclusions:

515 1) Although different regions of the Western Alps show a variable absolute amount of  
516 exhumation since 13.5 Ma, they share a common trend of doubling in exhumation rates at  
517 approximately 5 Ma. Providing assumptions on error values, it is possible to distinguish  
518 between areas where the rise in Alpine denudation took place at different periods within a 6.5  
519 to 2.5 Ma time frame.

520 2) The overall consistency between estimated denudation rates using sediment volumes  
521 (Kuhlemann, 2000), and bedrock thermochronology (this study) demonstrates that, although  
522 both records are fragmentary and error-prone, they are appropriate to describe the general  
523 exhumation history at the orogen scale since at least 13.5 Ma.

524 3) The maps of zircon and apatite fission-track ages share a pattern of young ages over an arc  
525 linking the External Crystalline Massifs, as well as in the area of the Lepontine Alps,  
526 suggesting that these areas underwent the strongest recent denudation in the Western Alps.  
527 The observed longer mean AFT lengths in the areas with young fission track ages further  
528 supports this conclusion.

529 4) This pattern fits with the trend of accelerated exhumation rates calculated from samples  
530 with paired zircon and apatite fission-track ages. This trend indicates that most of the Western  
531 Alps, in particular the external side of the arc, was on average exhumed faster after AFT  
532 closure than between the times of ZFT and AFT closure.

533

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542

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779 **Figure captions**

780

781 **Figure 1.** Evolution of sedimentation rates through time, reconstructed from the preserved  
782 volume of sediments originating from the Western and the Eastern Alps, respectively  
783 (modified from Kuhlemann et al., 2002).

784

785 **Figure 2.** (a) Simplified geologic map of the Western Alps (modified from Schmid et al.,  
786 2004). The study area (shown by bold outline) covers the geological units with the highest  
787 density of fission track ages (cf. Figure 3), limited to the east by the Austroalpine Silvretta  
788 nappe boundary at about 9°55' E. (b) Cross-section following north-south transect A-B across  
789 the central Swiss Alps (modified from Schmid et al., 1996).

790

791 **Figure 3-a.** Map of 635 AFT ages from the Western Alps, interpolated using a natural-  
792 neighbor algorithm. Morphotectonic regions and units referred to in the text: (1) Argentera,  
793 (2) Ecrins, (3) Belledonne, (4) Mont-Blanc, (5) Aar, (6) Chur area, (7) Gran Paradiso, (8)  
794 Sesia, (9) Dent-Blanche, (10) Penninic thrust, (11) Simplon fault, (12) Periadriatic line. AFT  
795 data are compiled from Bigot-Cormier 2002; Bogdanoff et al. 2000; Bürgi and Klötzli 1990;  
796 Carpéna and Caby 1984; Carpéna 1992; Ciancaleoni 2005; Flisch 1986; Fügenschuh and  
797 Schmid 2003; Fügenschuh et al. 1999; Giger 1991; Hunziker et al. 1992; Hurford and  
798 Hunziker 1989; Hurford 1986; Hurford et al. 1991; Keller et al. 2005; Knaus 1990; Lelarge  
799 1993; Leloup et al. 2005; Malusà et al. 2005; Michalski and Soom 1990; Pawlig 2001; Rahn  
800 et al. 1997; Sabil 1995; Schär et al. 1975; Schwartz 2000; Seward and Mancktelow 1994;  
801 Seward et al. 1999; Soom 1990; Steiner 1984; Timar-Geng et al. 2004; Trautwein 2000;  
802 Tricart et al. 2006; Viola 2000; Wagner and Reimer 1972; Wagner et al. 1977; Wagner et al.

803 1979; Weh 1998; as well as unpublished ages provided by M. Ford, D. Seward and our own  
804 data.

805

806 **Figure 3-b.** Map of 296 interpolated ZFT ages from the Western Alps. Numbers are as in  
807 Figure 3-a. ZFT data are compiled from Bernet et al. 2001; Bigot-Cormier 2002; Bürgi and  
808 Klötzli 1990; Carpéna 1992; Carpéna et al. 1986; Ciancaleoni 2005; Flisch 1986; Fügenschuh  
809 and Schmid 2003; Fügenschuh et al. 1999; Giger 1991; Hunziker et al. 1992; Hurford and  
810 Hunziker 1985; Hurford and Hunziker 1989; Hurford 1986; Hurford et al. 1991; Keller et al.  
811 2005; Michalski and Soom 1990; Rahn 1994; Schwartz 2000; Seward and Mancktelow 1994;  
812 Seward et al. 1999; Soom 1990; Vance 1999; Weh 1998; as well as unpublished ages  
813 provided by M. Ford, D. Seward and our own data.

814

815 **Figure 3-c.** Interpolated map of 258 mean apatite fission-track lengths ( $\mu\text{m}$ ) from the Western  
816 Alps. Short mean lengths ( $< 13 \mu\text{m}$ ) indicate slow passage of the sample through the AFT  
817 partial annealing zone, indicative of a slow exhumation rate. Long mean track lengths, in  
818 contrast, indicate rapid exhumation. Note the strong spatial overlap between mean track  
819 lengths  $>13 \mu\text{m}$  and AFT ages  $<\sim 10 \text{ Ma}$  (Figure 3-a), particularly in the Simplon and Chur  
820 areas, as well as more generally in the Mont-Blanc-Ecrins and the Argentera massifs.

821 Numbers are as in Figure 3-a. Apatite fission-track lengths compiled from Bigot-Cormier  
822 2002; Bürgi and Klötzli 1990; Ciancaleoni 2005; Giger 1991; Hunziker et al. 1992; Hurford  
823 and Hunziker 1989; Hurford 1986; Hurford et al. 1991; Knaus 1990; Malusà et al. 2005;  
824 Michalski and Soom 1990; Pawlig 2001; Rahn et al. 1997; Sabil 1995; Seward and  
825 Mancktelow 1994; Seward et al. 1999; Soom 1990; Timar-Geng et al. 2004; Trautwein 2000;  
826 Tricart et al. 2006; Wagner & Reimer 1972; as well as our own unpublished data.

827

828 **Figure 4.** Variation of exhumation rate ( $E_r$ ) through time, calculated from samples with  
829 paired AFT and ZFT ages. Samples with both ages younger than 35 Ma (i.e., Alpine cooling  
830 ages) are used to calculate an initial rate during the time between closure of the ZFT and AFT  
831 thermochronometers and a final rate for the time since closure of the AFT system (see text for  
832 details). The color scale presents the ratio between final and initial exhumation rates and  
833 enables to distinguish between localities where average exhumation rates have accelerated  
834 (ratio  $> 1$ ), remained steady (ratio  $\approx 1$ ) or decelerated (ratio  $< 1$ ) after AFT closure. Data  
835 points are labeled by their AFT age. Data origin is given in the legends of Figure 3-a and 3-b.  
836

837 **Figure 5.** Generic sketch of AFT isoage surface concept. (a) Denudation (i.e., removal of  
838 material) occurring between times  $t_1$  and  $t_2$  over the present day topography is reflected by the  
839 migration of shallow isotherms, downwards with respect to the exhuming rock mass such that  
840 a rock particle is cooled during exhumation (see definitions in Ring et al., 1999). The 120 - 60  
841 °C AFT partial annealing zone is shifted downwards, and so are the AFT closure temperature  
842 (the temperature at which the first track is recorded) and the AFT closure surface (the surface  
843 linking all samples crossing the closure temperature at a given moment). (b) Former closure  
844 surfaces become isoage surfaces, younging downwards and intersecting the topography.  
845

846 **Figure 6.** Steps toward the interpolation of isoage surfaces. A neighborhood search of  
847 significant age-elevation relationships (AER) is performed within 3 km around each data  
848 point (a, b). If the correlation coefficient between age and elevation is not statistically  
849 significant at the 95 % confidence level (b), the radius for selection of points is increased  
850 stepwise up to a maximum of 15 km (c). The  $A_0$  and  $A_1$  parameters defining the regression  
851 lines are used to interpolate the elevation of isoage surfaces between 1 Myr before the oldest  
852 age selected ( $A_{max}$ ) and 1 Myr after the youngest age selected ( $A_{min}$ ). Finally, isoage surfaces

853 are obtained by interpolation of isoage point arrays combining the results of neighborhood  
854 AER search and the elevation of isoage contours (d). The figure shows a zoom of the  
855 Lepontine area and the sources of data points are as in Figure 3a.

856

857 **Figure 7.** Six examples of isoage surfaces among the 13 obtained between 14 and 2 Ma.

858 Following a natural-neighbor interpolation between isoage points, the grid is clipped with a  
859 mask at 15 km to reduce the number of pixels located far from any source of information. The  
860 color scale represents the elevation in meters above sea level (note that the scale is different  
861 for each panel). The overall elevation of old isoage surfaces (e.g., 11 Ma; 14 Ma) is higher  
862 than the elevation of younger isoage surfaces (2 Ma; 4 Ma) which is in agreement with the  
863 generic sketch in Figure 5.

864

865 **Figure 8.** Areas with continuous isoage surface coverage. Eight areas with isoage surfaces  
866 covering 4 to 10 Myr were obtained by comparing the area covered by the 13 isoage surfaces  
867 obtained between 14 and 2 Ma (Figure 6). Different periods of time are documented in  
868 different areas, as indicated in the legend, depending on the ages accessible at outcrop.

869

870 **Figure 9.** Calculation of denudation rate from the elevation difference of isoage surfaces. (a)  
871 Map of the elevation difference between the 5 and 4 Ma isoage surfaces. (b) In this example,  
872 values of elevation difference are extracted from the area of continuous isoage surface  
873 coverage located on the Mont-Blanc massif (area 4 in Figure 8), and plotted in a frequency  
874 histogram. The pixels with a negative value (in black on the map) cannot be used to infer  
875 denudation rates and are discarded. The average distance between isoage surfaces is  
876 calculated over the remaining histogram and considered to be equivalent to the amount of  
877 exhumation affecting the Mont-Blanc area during the corresponding period.

878

879 **Figure 10.** Comparison between the estimates of average denudation rate (recorded in  
880 sediment volume) and exhumation rate (using AFT isoage surfaces, this study) over the  
881 Western Alps. The average Western Alps denudation rate calculated by Kuhlemann (2000) is  
882 the ratio between the peri-Alpine sedimentation rates (Figure 1) and the provenance area. The  
883 exhumation rate was estimated over 8 regions of the Western Alps by the isoage surface  
884 technique (Figures 5 to 9). Both the envelope of exhumation trend and the denudation curve  
885 show an increase centered around 5 Ma. See sections 6.3. and 6.4. for a discussion of the  
886 features observed in exhumation rate trends.

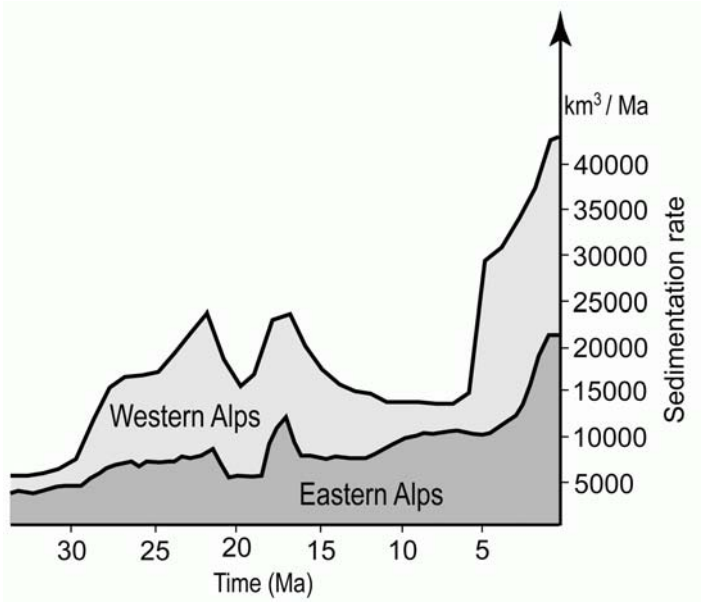


Figure 1

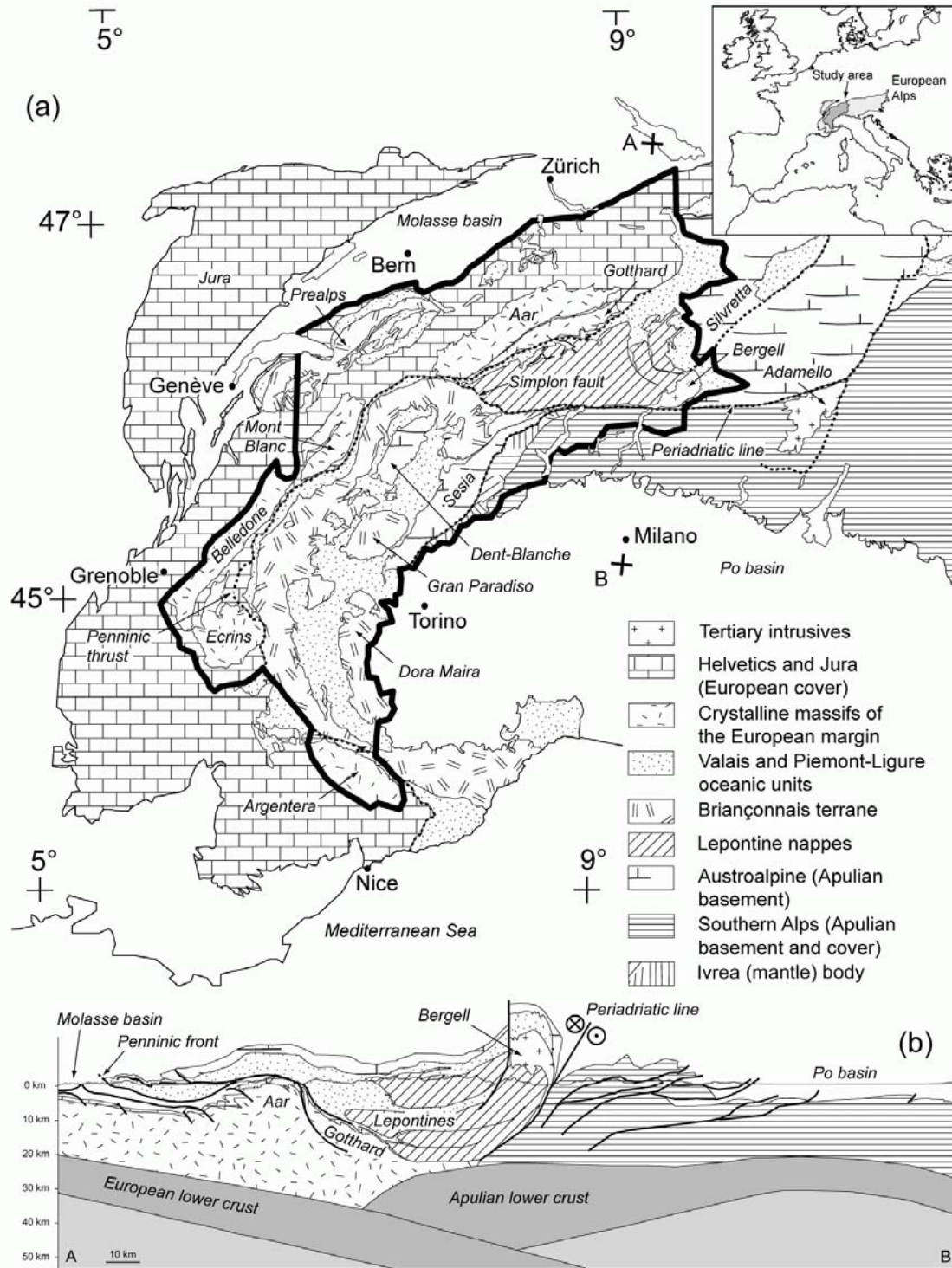


Figure 2



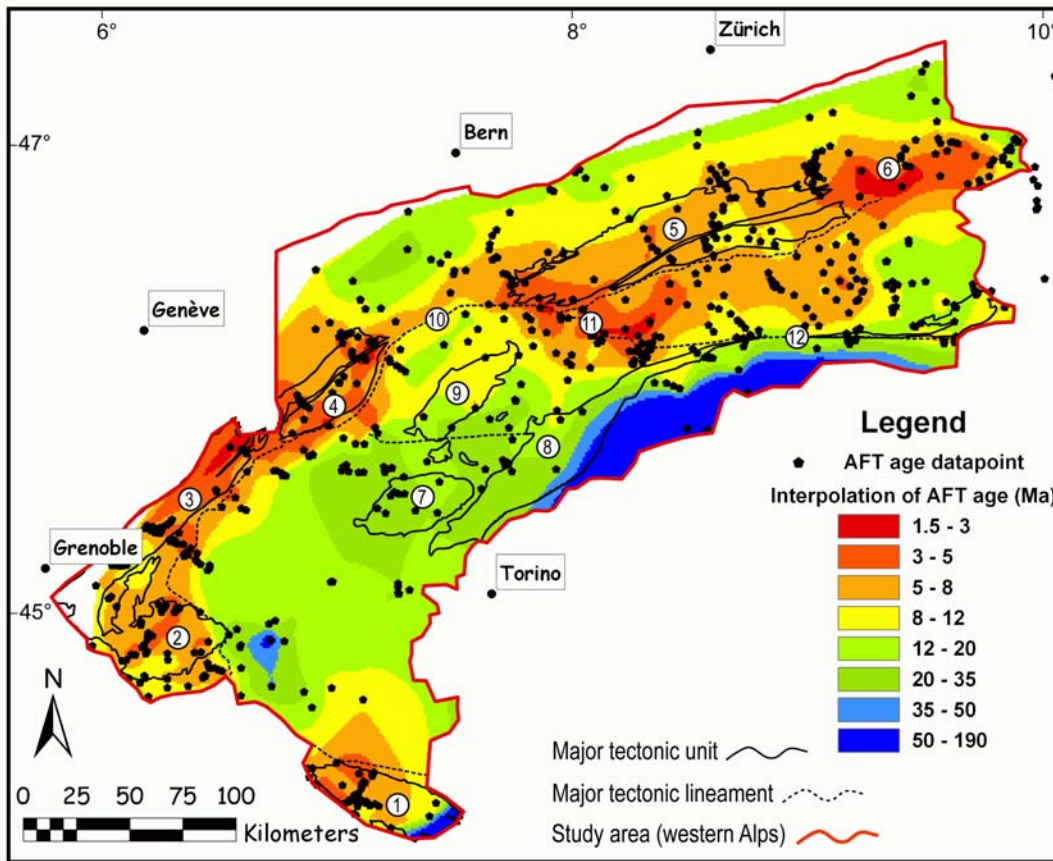


Figure 3-a

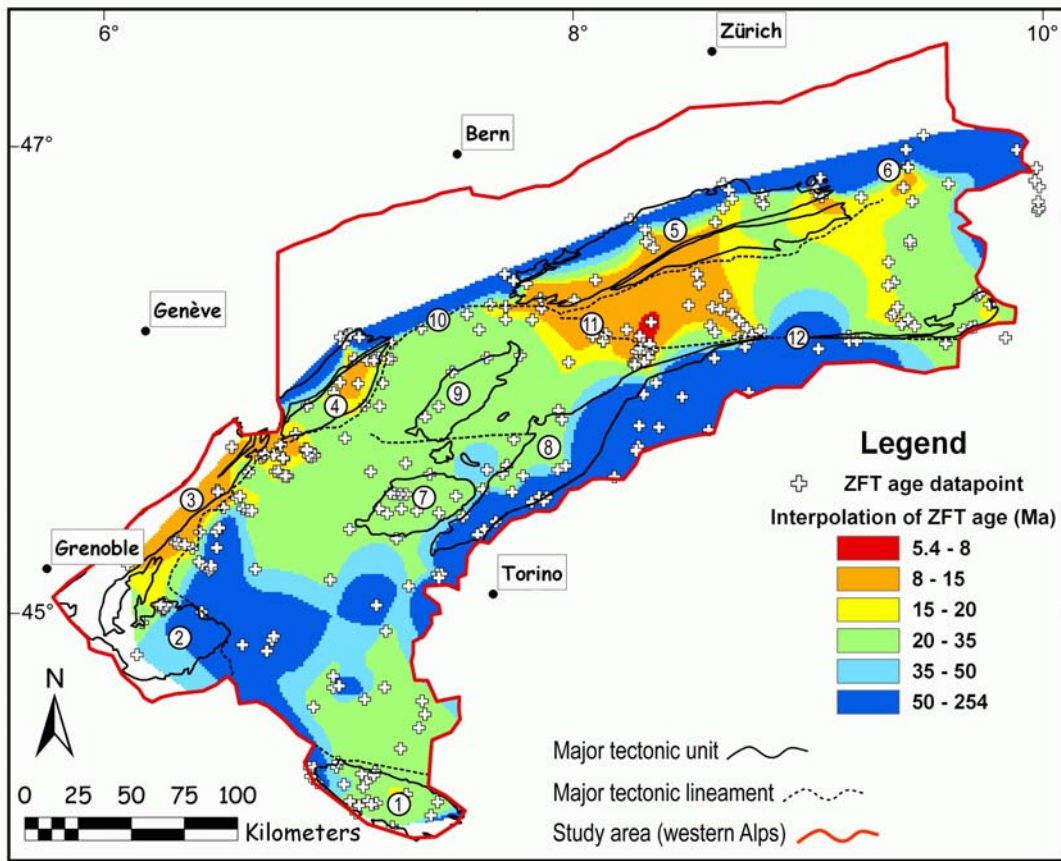


Figure 3-b

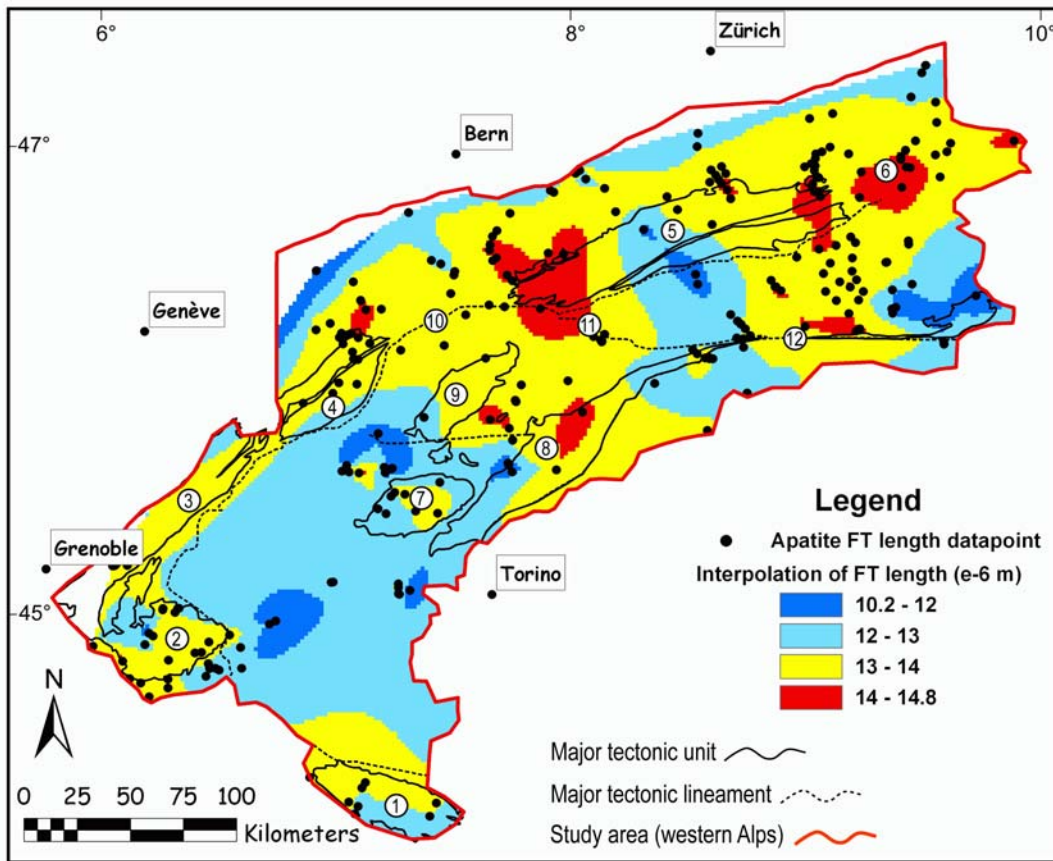


Figure 3-c

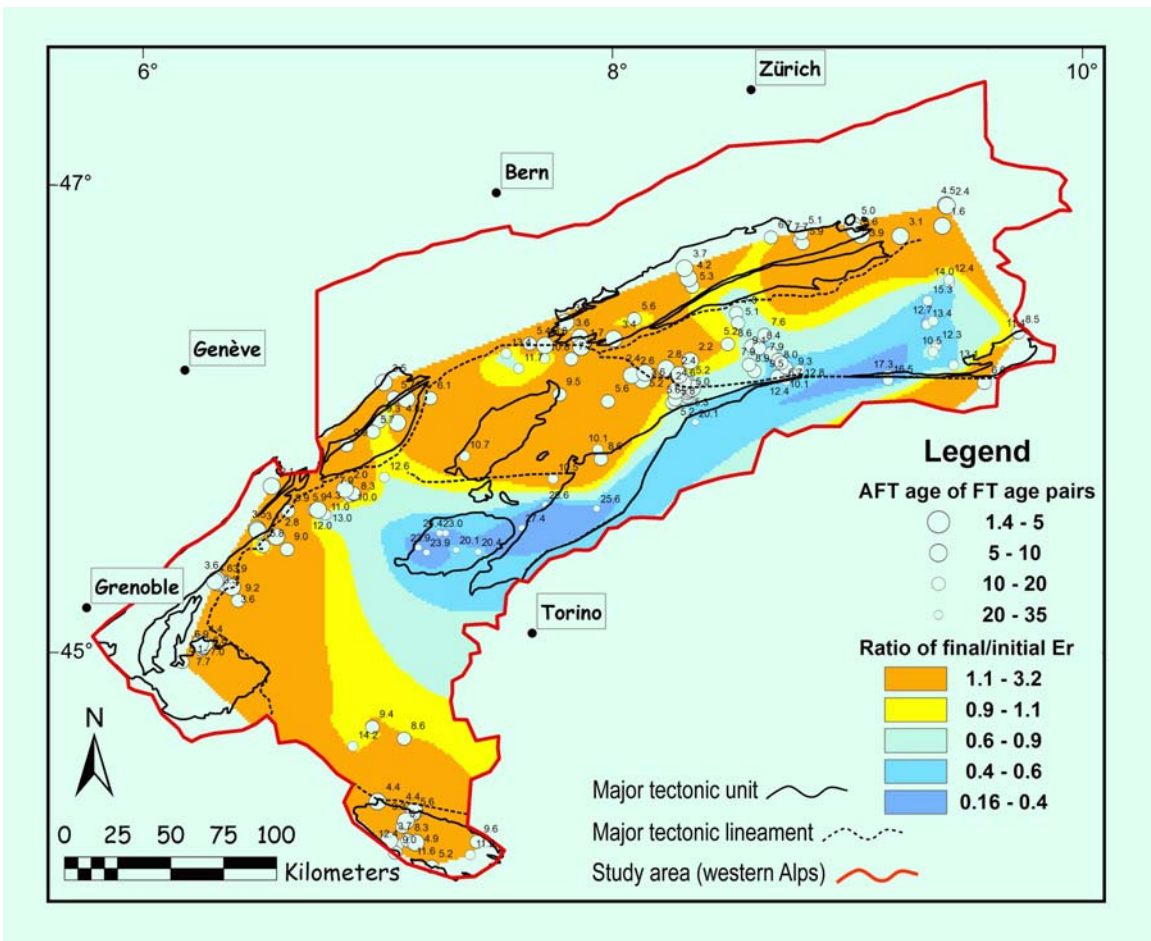


Figure 4

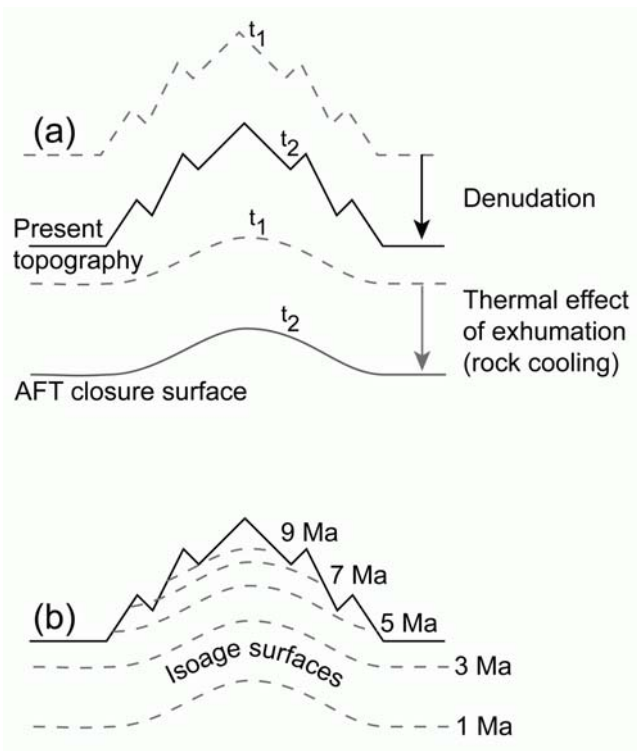


Figure 5

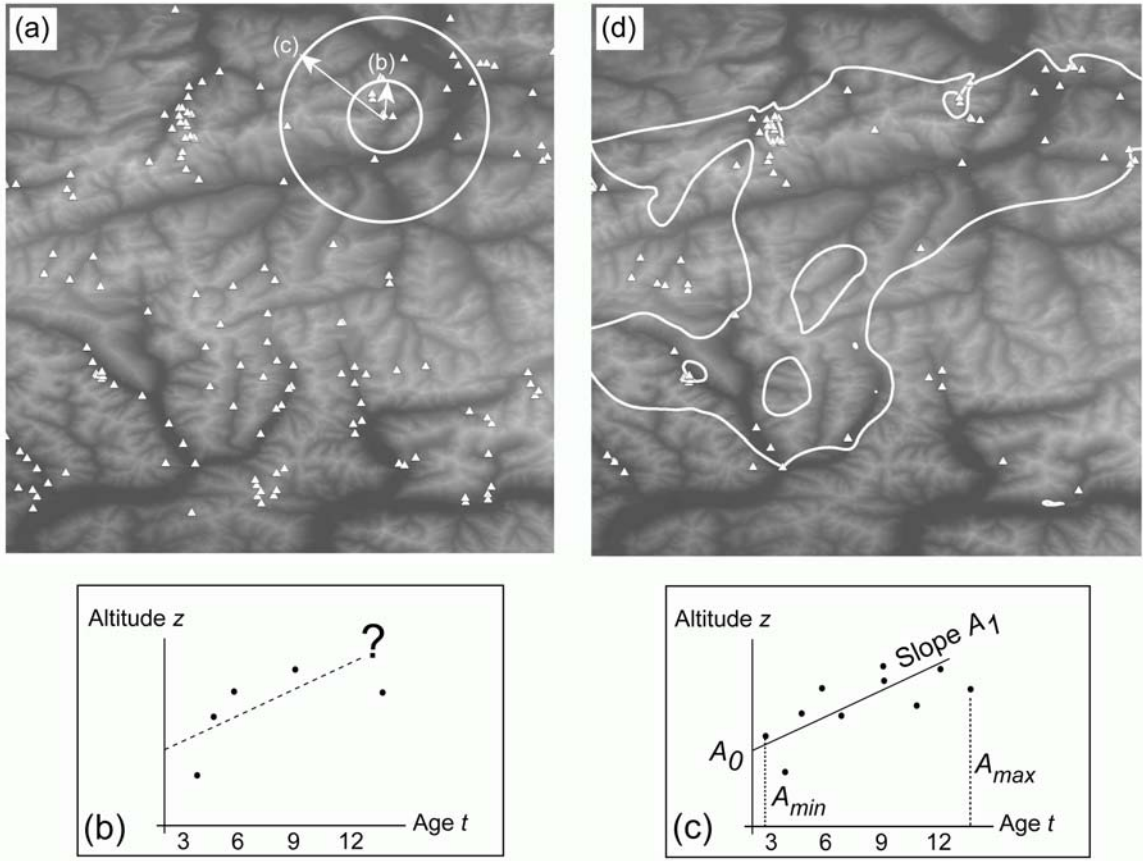


Figure 6



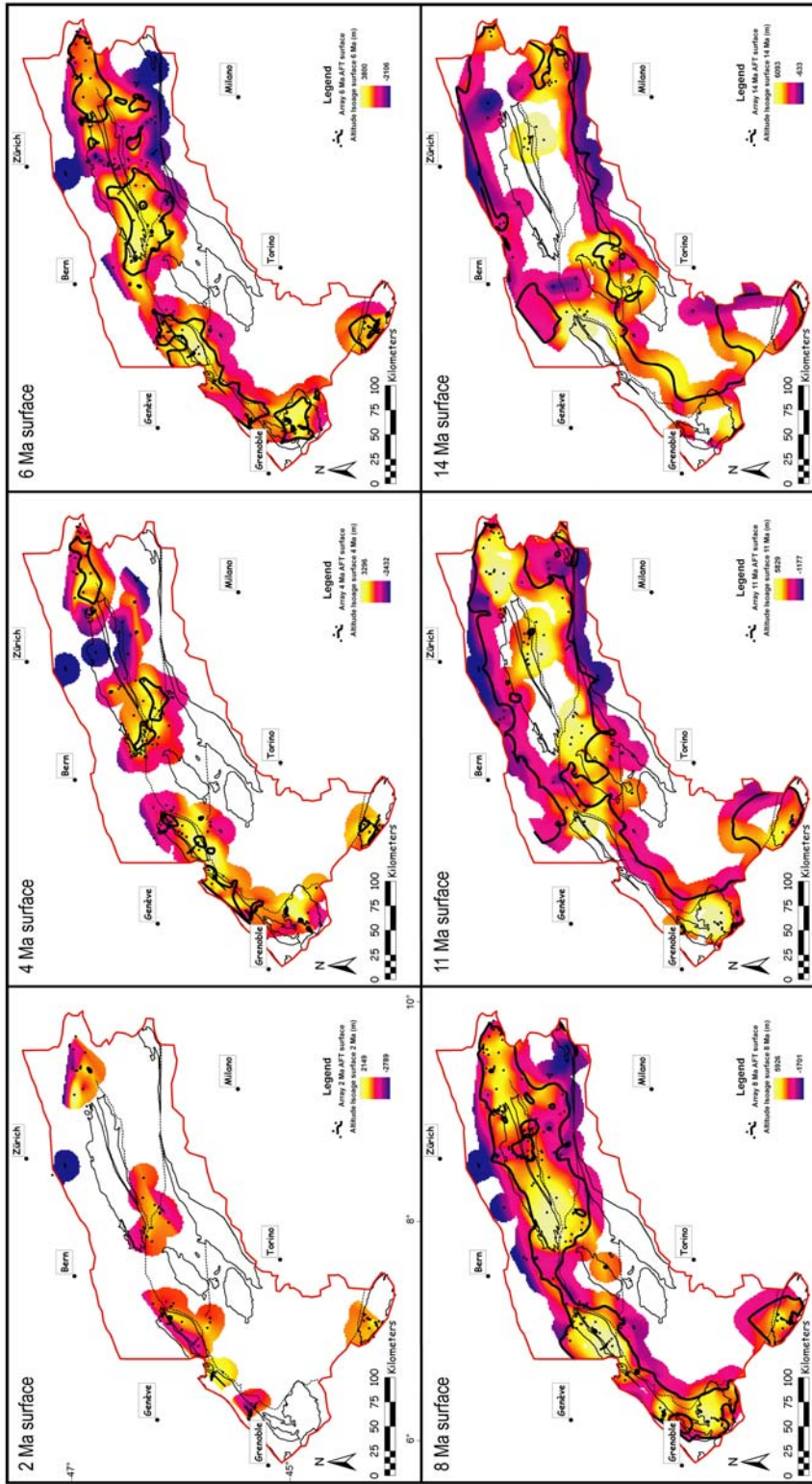


Figure 7

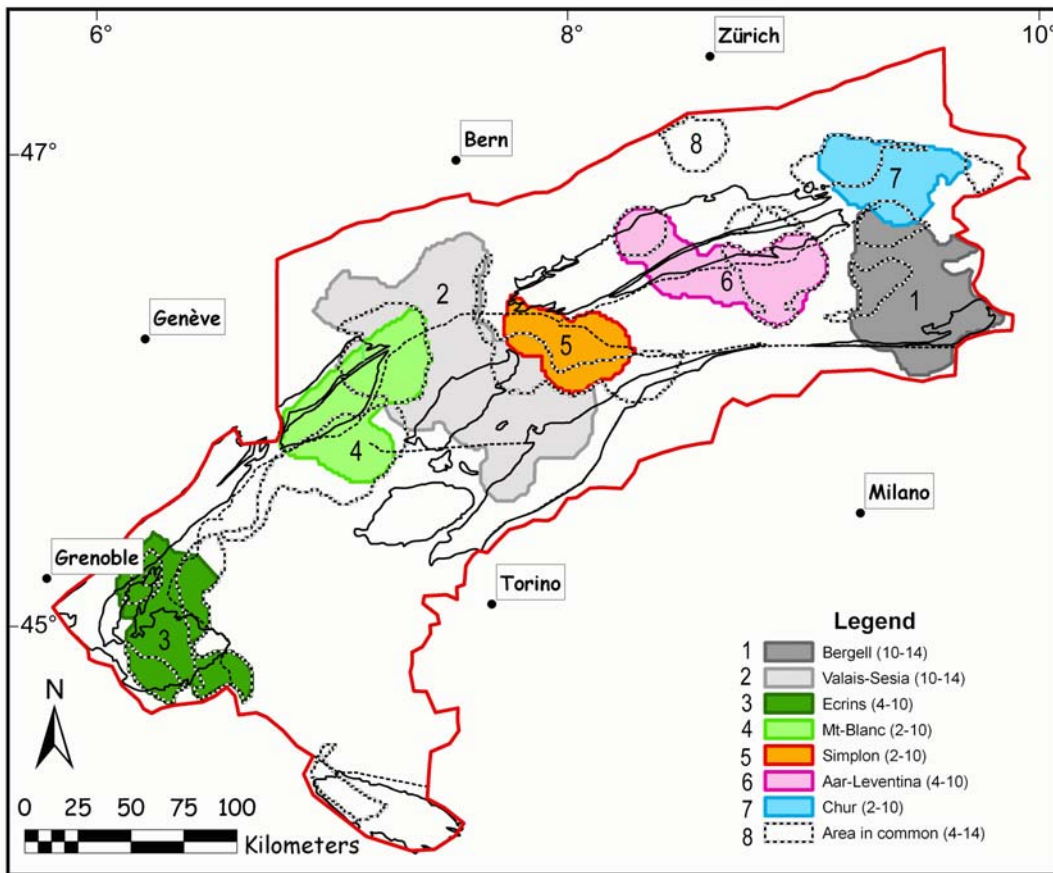


Figure 8



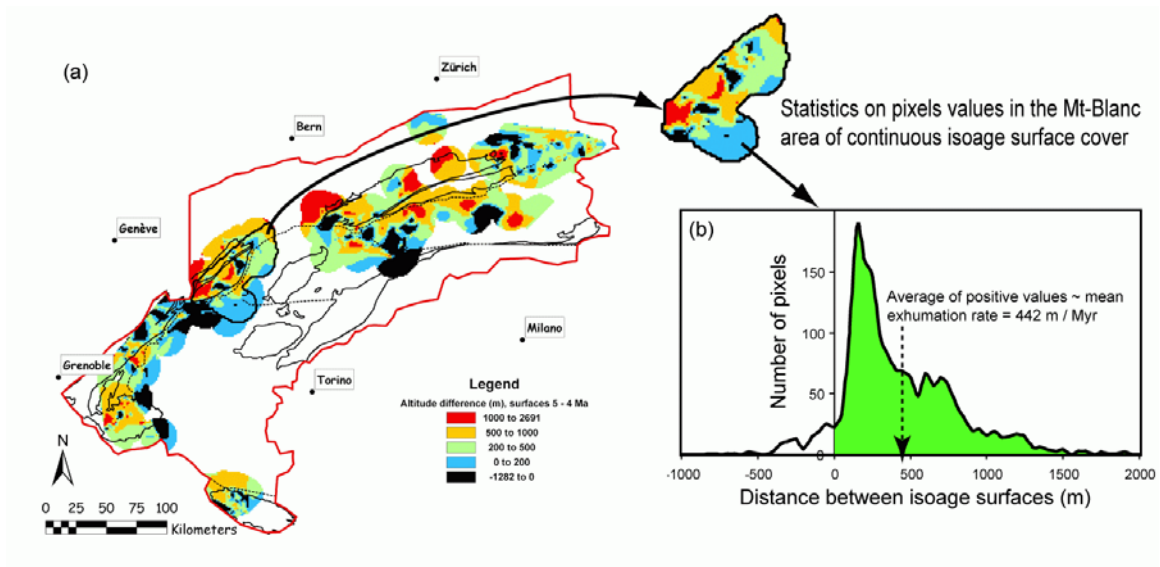


Figure 9

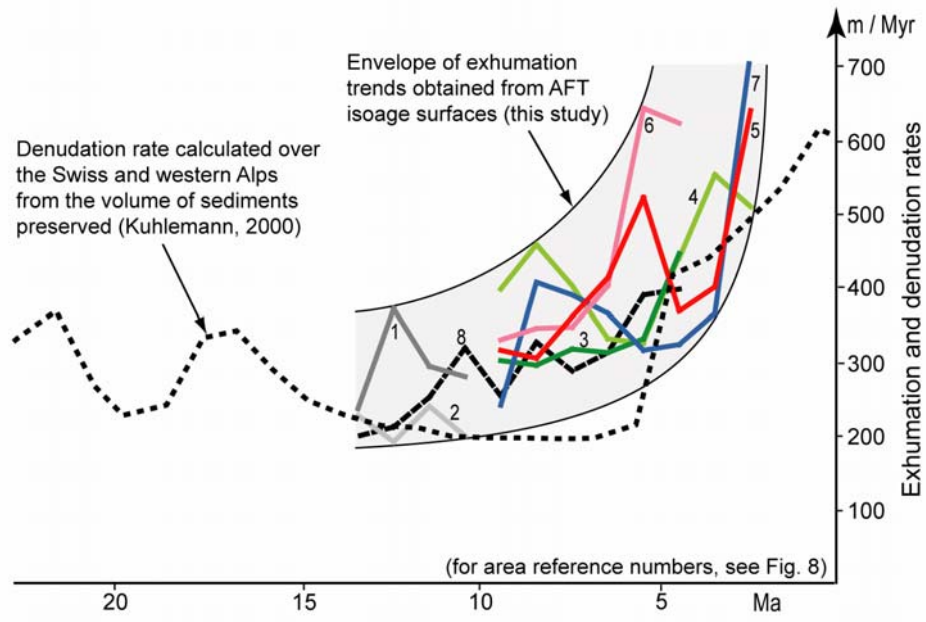


Figure 10