Rapid exhumation in the Western Alps driven by Slab Detachment and Glacial Erosion

Inverse Approach

Our method to convert thermochronometric ages to exhumation rates combines a thermal model, to predict temperature, with a closure temperature calculation for each thermochronometric system (Fox et al., 2014). A thermal model is used to predict temperature in space and time, as well as a material-point cooling rate, from which we calculate the characteristic closure temperature and its depth. The exhumation rate or, equivalently, the surface erosion rate at this point in space is a function of time, $\dot{e}(t)$ and is related to the age, t , through a travel-time expression,

$$\int_0^t \dot{e}(t)\,dt = z_c \qquad (1)$$

We parameterize exhumation rate at a single point in space as a piecewise constant function in time over a set of specified time intervals, and given the depth to the closure temperature, each age can be expressed as a linear equation. A suite of *M* ages can be expressed as a system of linear, independent, equations:

$$A\dot{e} = z_c \qquad (2)$$

where z_c is a vector of length M, $\dot{e}$ is a vector of unknown exhumation rates, whose length is the product of the number of data and the number of time intervals, and A is a sparse matrix whose components are simply the time interval lengths that sum to the measured age. In general each age is obtained at an independent location in space and, as we regard exhumation rate as variable in space, each row in Equation 2 is an independent equation. To be solvable, these independent equations must be coupled. We do so by requiring that exhumation rate be correlated in space for a given time interval. This can be imposed by defining an *a priori* covariance matrix for the exhumation rate vector and obtaining the maximum likelihood solution (Tarantola, 2005). The covariance matrix for each time interval is constructed using the separation distance between the ith and jth data, d_{ij}, and an exponential correlation function,

$$C_{ij} = s_{\dot{e}}^2 \exp\left(- d_{ij} / l \right) \qquad (3)$$

where l is a specified correlation length. We also specify an a priori variance for the exhumation rate, $s_{\dot{e}}^2$, but its primary influence is as a weighting factor for the data uncertainty. It is assumed that exhumation rate is not correlated in time, so there is an independent matrix of form (3) for each time interval. These can be combined into a global matrix, setting cross-terms to zero. The maximum likelihood estimate for the exhumation rate is then (30):

$$\dot{e} = \dot{e}_{pr} + CA^T \left(ACA^T + C_e \right)^{-1} \left(z_c - A\dot{e}_{pr} \right) \qquad (4)$$

where $\dot{e}_{pr}$ is the a priori expected value of the exhumation rate, used to reduce the model to a zero expected value, and C_e is a diagonal matrix containing the estimated data uncertainty which we obtain from the analytical errors in the measurements. The depth to a closure isotherm is calculated from a one dimensional finite difference solution to the advection-diffusion equation for heat transfer to an isothermal boundary at the Earth's surface. Closure depth is evaluated at the time corresponding to the age of the sample and takes into account the cooling-rate dependence of closure temperature. Although the thermal calculation is done only in the depth dimension, we correct the solution to take into account the perturbation of the closure isotherm due to topography using a spectral method (Fox et al., 2014). The thermal model is calibrated to the measured present day surface heat flux (Bodmer and Rybach, 1984), although we recognize that there is large uncertainty in these data and so investigate the sensitivity of our results to surface heat flow. The temperature solution depends on the exhumation rate, so the problem is non-linear and we obtain the solution by direct iteration; convergence typically occurs in less than ten iterations. We also calculate a parameter resolution matrix as (Tarantola, 2005)

$$R = CA^T \left(ACA^T + C_e \right)^{-1} A \quad . \qquad (5)$$

The resolution matrix relates an exhumation rate to all other exhumation rates in space and time, so that for perfectly resolved parameters *R* is equal to the identity matrix. To simplify presentation, we integrate the resolution matrix across the spatial dimension. This thus ignores spread in space, but provides a measure of how well the exhumation rate at a single point is resolved in a particular time interval. A resolution value of 1.0 indicates perfect resolution; lower values indicate spread or averaging between time intervals (Fig. 3).

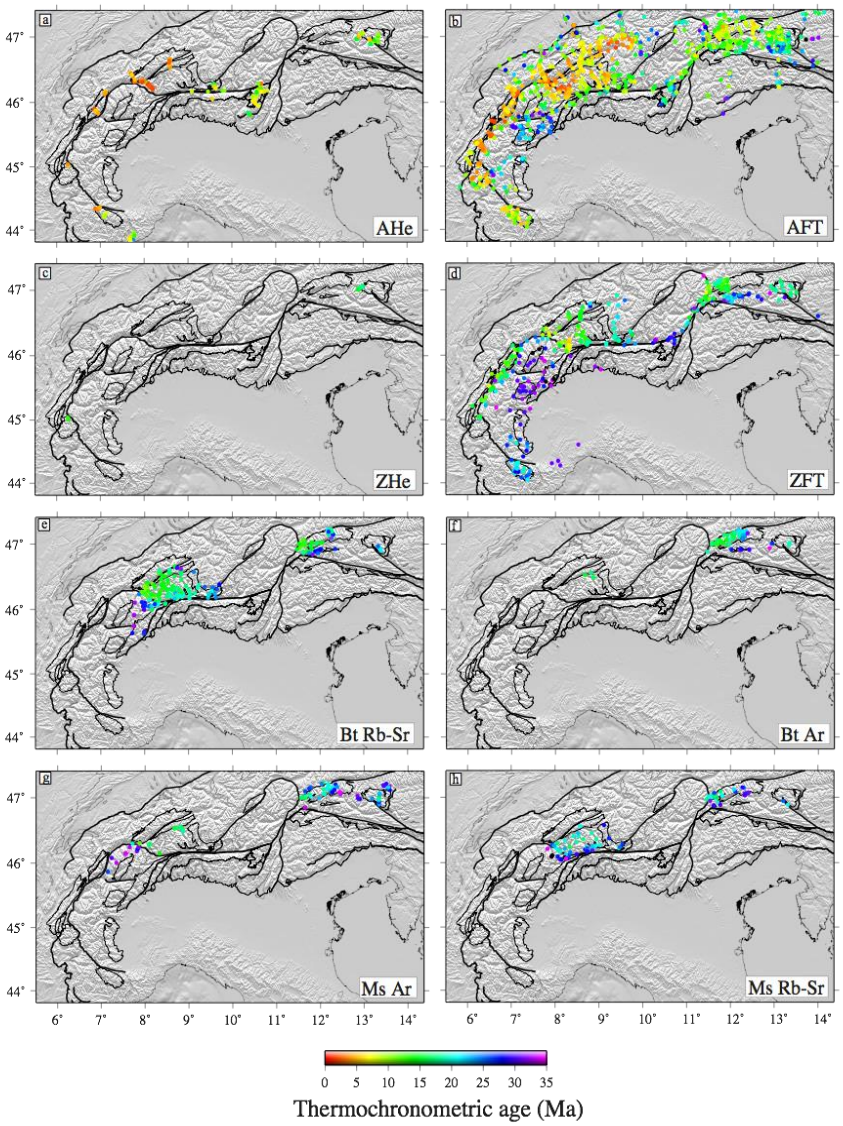

Figure DR1: Thermochronometric ages from the Alps used in our analysis. Ages that have been interpreted as that were not considered (due to fluid flow or poor reproducibility) in the original manuscripts are not included. Each plot shows ages for a specific mineral system. (a) Apatite (U-Th)/He, (b) apatite fission track ages, (c) zircon (U-Th)/He, (d) zircon fission track ages, (e) Rb-Sr in biotite, (f) 39Ar–40Ar and K/Ar in biotite, (g) 39Ar–40Ar and K/Ar in biotite, and (h) Rb-Sr in muscovite. Sources are referenced below.

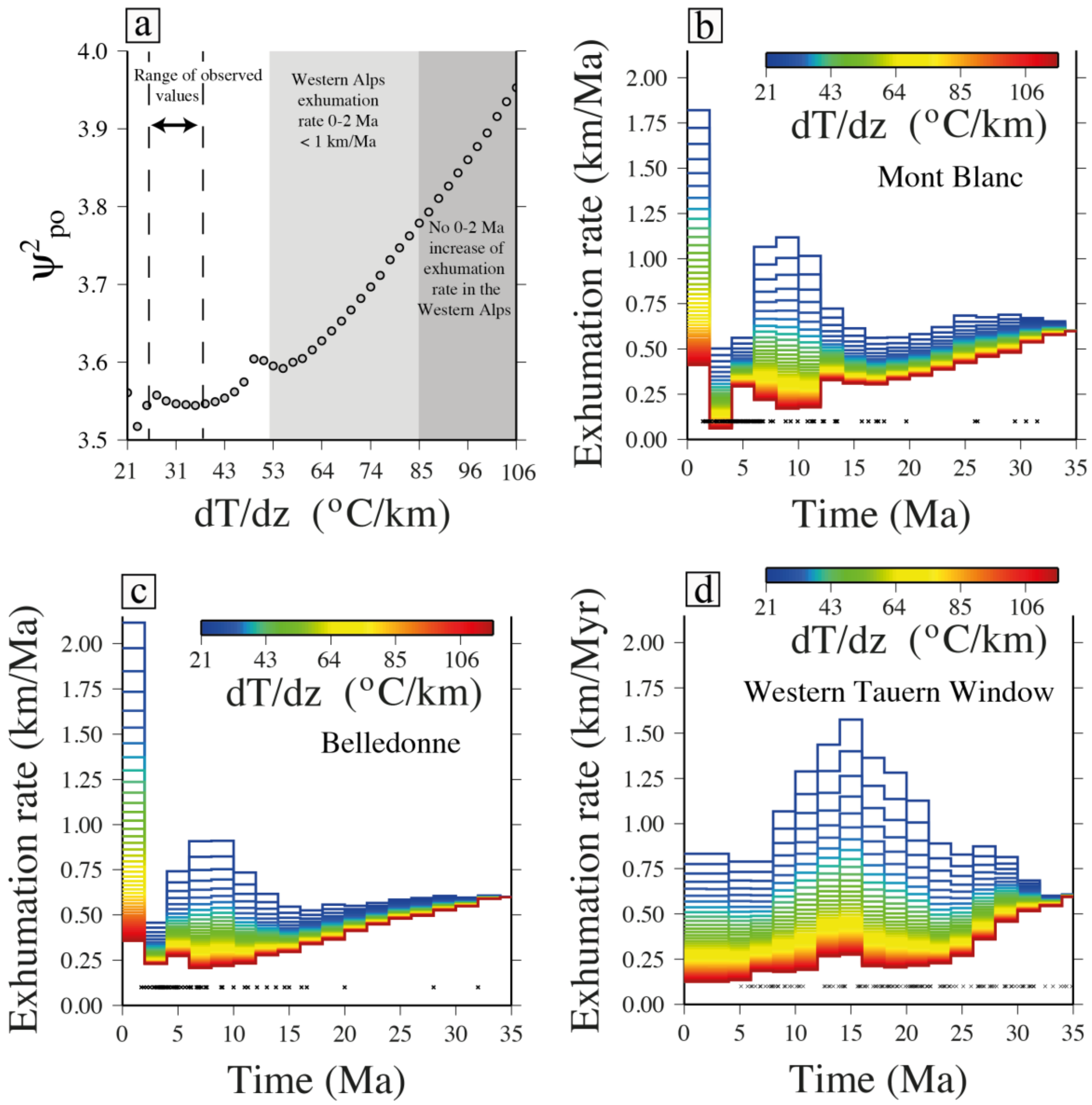

Figure DR2: Sensitivity of exhumation rate to modeled geothermal gradient. In all models, the initial, imposed geothermal gradient increases towards the present day in response to exhumation-driven advection. Although we specify initial gradient, we present results in terms of final gradient for comparison to observations. (a) A norm of the misfit between measured ages and predicted ages , ψ^2_{po}, for inversion results as a function of the predicted present day surface geothermal gradient using the prior exhumation rate, which is characteristic of the average over the study area. Observed gradients (Bodmer and Rybach, 1984) are in the range of 22 °C/km to 35 °C/km, but are notoriously poorly determined in mountainous terrain such as the Alps. Our best fit to the observed ages is found in the range of the observations, or even lower. High exhumation rates in last time interval persist for all models, but are not significant once geothermal gradients are over 85 °C/km. Example exhumation histories are given for (b) Mont Blanc region and (c) Belledonne massif. Note large increase in exhumation rate in last time step for geothermal gradients in range of observation, but only a small increase if geothermal gradients are two to three times higher than estimated from borehole and tunnel temperatures.

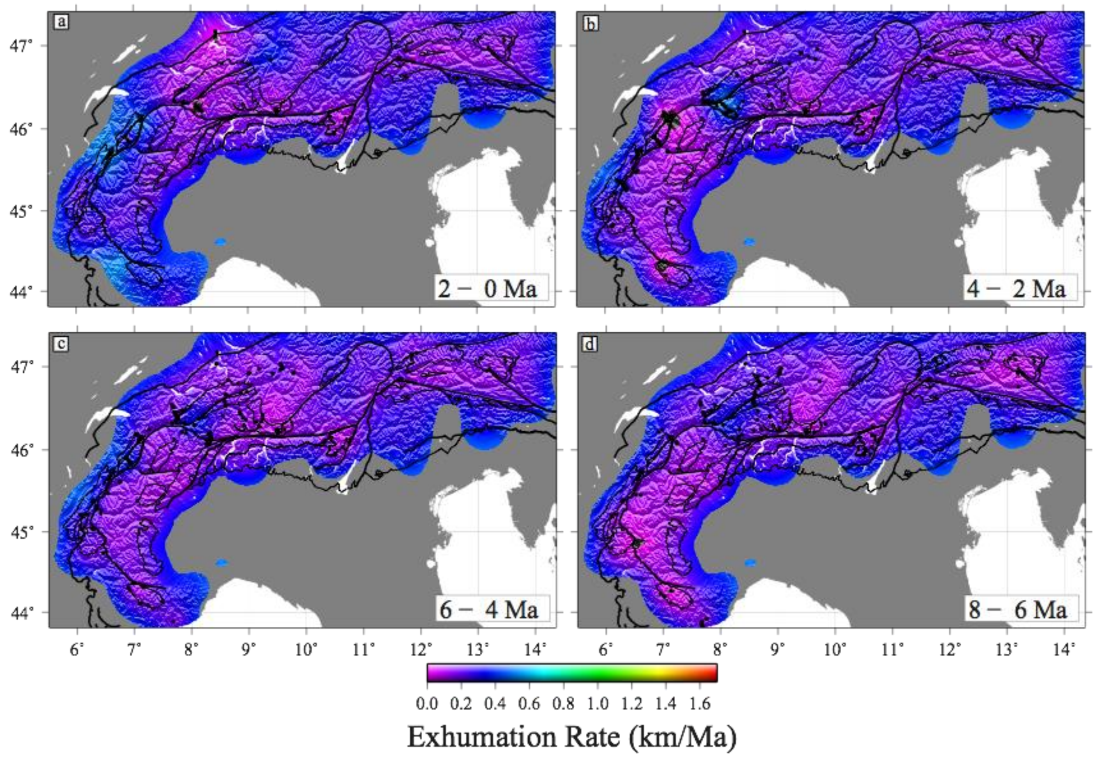

Figure DR3: Extreme geothermal gradient model. Spatial and temporal distribution of exhumation rate for an inversion with a thermal model that predicts a present day geothermal gradient of 100 ˚C/km. There is little to no increase in exhumation rate from 2 Ma to present in the Western Alps. However, exhumation rates are everywhere very low compared to other studies and this predicted geothermal gradient is much higher than observations, so we suggest that this model is unlikely to represent reality.

Parameter	Parameter symbol	Value	Units
Thermal model parameters			
Elevation of upper boundary	z_0	1475	m.a.s.l
Temperature of upper boundary	T_0	4	°C
Basal heat flux	q_l	40	mW m^{-2}
Thermal diffusivity	κ	35	km^2/Myr
Thermal conductivity	k_l	2.6	$Wm^{-1}K^{-1}$
Model thickness	l	90	km
Onset of exhumation	t^*	34	Ma
Exhumation rate	$\dot{e}_{pr}$	0.6	km/Myr
Inversion parameters			
Prior exhumation rate	$\dot{e}_{pr}$	0.6	km/Myr
Prior exhumation rate standard deviation	σ_{pr}	0.1	km/Myr
Time interval length	ΔT	2	Myr
Correlation length scale parameter	xL	25	km

Table DR1. Parameters used in the analysis. Thermal model parameters used to calculate closure depths and the parameters required for the inversion method described in detail in Fox et al., 2014.

Movie S1. Results of the inversion for time steps of 2 Myr. The exhumation rate function we recover is highly variable in space and through time. We are only able to resolve such a complex exhumation function due to the exceptional quantity of thermochronometric data.

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