Tectonophysics 649 (2015) 115–129

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

A Fourier approach for estimating and correcting the topographic perturbation of low-temperature thermochronological data

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ARTICLE INFO

Article history:
Received 7 August 2014
Received in revised form 26 February 2015
Accepted 2 March 2015
Available online 27 March 2015

Keywords:
Thermochronology
Isotherms
Topographic perturbation
Age–elevation profile

ABSTRACT

Thermochronology is a unique tool to reconstruct the long-term exhumation history of outcropping rocks. Pronounced (palaeo-) topography can markedly perturb near-surface isotherms, which can result in erroneous exhumation histories derived from age–elevation relationships but also offers the possibility to reconstruct palaeo-topography. Here we use a synthetic dataset to illustrate the complex non-linear relationships between the degree of topographic perturbation of thermochronological ages on one hand, and exhumation rate, geothermal gradient, and topographic wavelength and relief on the other. The dataset reveals that, in theory, relief changes can be retrieved for wavelengths as low as 5 km, and wavelength changes are possible to detect for relief as low as 0.5 km. In addition, the data attest that even in regions characterised by very slow exhumation rates (e.g. 0.03 km/Ma), changes in palaeo-topography can be successfully retrieved. Coupling of this dataset with a Fast Fourier Transform (FFT) algorithm to decompose complex 2D topography into sinusoidal functions allows a rapid and accurate estimation of the topographic perturbation and resulting thermochronological ages assuming steady-state exhumation. This coupled method was successfully implemented to (i) predict most promising sample sites for the estimation of palaeo-topography and (ii) correct exhumation rates derived from non-vertical age–elevation profiles.

1. Introduction

The interpretation of low-temperature thermochronology data strongly depends on the shape of critical isotherms, which is a function of topography and exhumation rate among other parameters (e.g. Braun, 2003; Ehlers and Farley, 2003; Mancktelow and Grasemann, 1997). In addition, it has been shown that spatially variable rock advection, rock thermal parameters and groundwater flow potentially modify the shape of near-surface isotherms (e.g. Glotzbach et al., 2009; Whipp and Ehlers, 2007). Assuming that heat conduction dominates heat transfer and exhumation (used in this paper to refer to a long-term regional process; excluding local incision) is spatially constant, near-surface isotherms will follow the topography in a dampened fashion (e.g. Stüwe et al., 1994; Turcotte and Schubert, 1982) (Fig. 1a). As a result, cooling paths and resulting thermochronological ages differ for samples taken along a horizontal profile (e.g. along a tunnel), with youngest ages below ridges and oldest ages in the valleys. If isotherms are flat, ages are constant along a horizontal profile and linearly increase with elevation, with the slope of the age–elevation relationship (AER) corresponding to the exhumation rate. The perturbation of isotherms decreases the age of ridge samples; exhumation rates derived from AER of non-vertical sample profiles will therefore be overestimated (e.g. Braun, 2002a; Stüwe et al., 1994) (Fig. 1d). Assuming that relief decreases after closure of the thermochronometer, the resulting AER would be vertical if the present-day relief equals the former perturbation of the elevation of the effective closure temperature (T_c). In the rare case that the former perturbation of the T_c exceeds the actual relief, ridge samples would be younger than valley samples, resulting in an inverted AER (Braun, 2002a).

At the same time, thermochronological data, in particular when collected along horizontal profiles, contain important information about palaeo-relief (e.g. Reiners, 2007). The absence of age perturbation along a horizontal profile crossing pronounced topography can be diagnostic for reduced palaeo-relief and vice versa. Several studies have estimated palaeo-relief in different geological settings, including slowly and rapidly exhuming mountain belts (Braun and Robert, 2005; Ehlers et al., 2006; Foeken et al., 2007; Glotzbach et al., 2008, 2009, 2010, 2011; Herman et al., 2007; House et al., 1998, 2001; Persano et al., 2002; Reiners et al., 2003; Valla et al., 2011a,b, 2012). Along with these applications, analytical and numerical modelling solutions were developed to take into account the topographically induced perturbation of thermochronological data and correct derived

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http://dx.doi.org/10.1016/j.tecto.2015.03.005

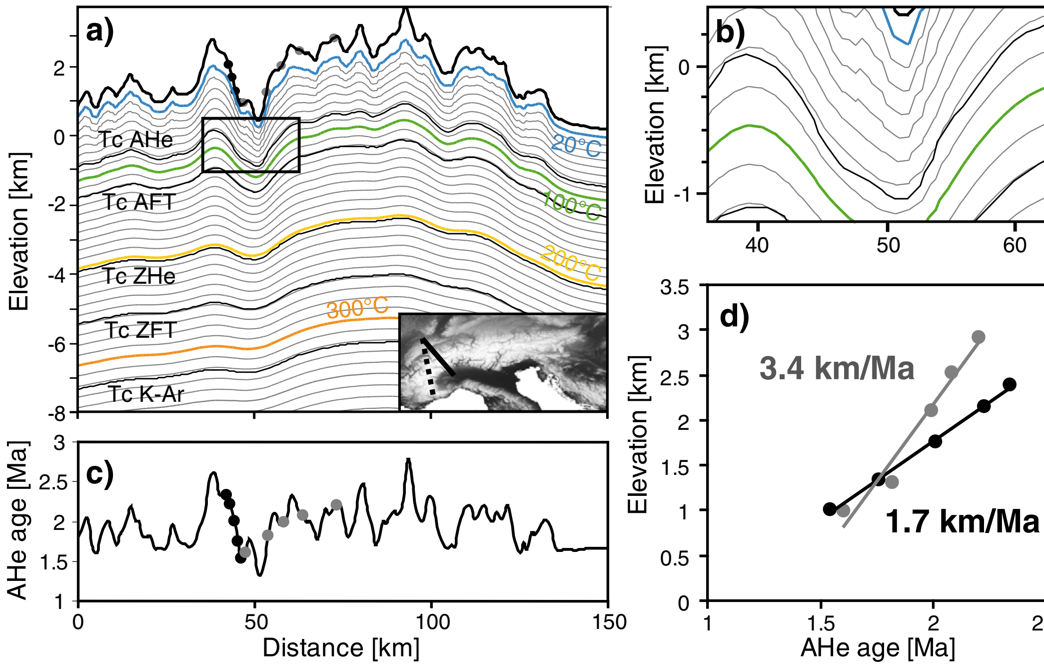

Fig. 1. a) Topographic profile across the Central Alps (for location see continuous black line in inset map), corresponding isotherms and closure temperatures (T_c) for different thermochronometers for an exhumation rate of 1 km/Ma and an ICGG of 20 °C/km (calculated with the thermo-kinematic code PECUBE). Note that changes in the near-surface geothermal gradient led to spatial variations in T_c, which deviates slightly from fixed isotherms. Inset map shows a DEM of the European Alps and location of the cross section. b) Detail showing spatial variations of the AHe closure temperature (80–90 °C) related to differences in near surface geothermal gradients. c) AHe ages along the topographic transect, black and grey dots mark locations and ages of the AERs in a and d. d) AHe age–elevation profiles for two sample transects implying apparent exhumation rates of 1.7 and 3.4 km/Ma (real exhumation rate is 1 km/Ma), for location see a.

exhumation rates and palaeo-topographic estimations (Braun, 2002a,b, 2003; Braun et al., 2012; Centeno, 2005; Ehlers and Farley, 2003; Huntington et al., 2007; Mancktelow and Grasemann, 1997; Stüwe et al., 1994; Wang and Zhou, 2009).

Mancktelow and Grasemann (1997) and Braun (2002a) investigated how relevant input parameters including topographic wavelength and amplitude, geothermal gradient, exhumation rate and the duration of relief change affect the magnitude of isotherm perturbation. Their results predict that even low exhumation rates (e.g. 0.3 km/Ma) combined with long wavelengths (50 km) are capable to perturb near-surface isotherms, resulting in an overestimation of corresponding AER. These studies presented correction factors that can be used to correct AER for the effect of topographically induced perturbation of thermochronological ages. They, however, assume a finite 1D sine-shaped topography and neglect the influence of 2D topographic features, and therefore only roughly estimate the topographic perturbation of thermochronological data taken along complex topography. Spectral analysis of thermochronological ages and elevation profiles can be used to consider the impact of complex 2D topography and derive mean exhumation rates and relief changes (Braun, 2002b). Application of this method, however, requires 30–50 samples along a topographic profile spanning over several tenth of kilometres. As an example, Centeno (2005) applied a spectral analysis to AHe ages along a 120 km long horizontal profile along the Torngat Mountains in Canada to estimate the age of topographic evolution. Wang and Zhou (2009) presented a method to estimate the shape of 1D palaeo-topography independently of the relationship between present-day and palaeo-topography. They reconstruct the shape of palaeo-isotherms using the age and elevation of a large dataset, assuming invariant exhumation rates and T_c. Taking an analytical description of the relationship between isotherms and topography, the palaeo-topography can be reconstructed after decomposition of the palaeo-isotherms into a set of Fourier series. The vertical precision of this palaeo-topography estimation depends on the analytical error of the sample age and the sample density, whereas the latter limits the horizontal resolution of the estimation (Wang and Zhou, 2009). A more general method to extract the exhumation and topographic evolution from thermochronological data is to numerically model thermochronological data by solving the heat production–diffusion–advection equation in 3D, such as the finite element code PECUBE (Braun, 2003). The code predicts thermochronological data from modelled tT-paths, and combined with a neighbourhood algorithm inversion (Sambridge, 1999a,b), enables to efficiently search and estimate exhumation rates and relief evolution (e.g. Braun and Robert, 2005; Braun et al., 2012; Fox et al., 2014a; Glotzbach et al., 2011; Herman et al., 2007, 2009, 2010; Reverman et al., 2012; Valla et al., 2010, 2011a,b).

In this study we present a new and easily applicable tool to estimate the topographic perturbation of thermochronological ages in one or two dimensions and correct exhumation rates derived from an AER. Contrary to previous approaches, we measure directly the perturbation of thermochronological data, thus avoiding possible inherent uncertainties from the assumption of a fixed closure temperature (Fig. 1a, b). To achieve this, we first calculate the topographically induced age perturbation of different low-temperature thermochronometers as a function of exhumation rate, geothermal gradient, topographic wavelength and topographic amplitude using PECUBE. The resulting synthetic dataset is used to answer the following questions: (i) What are minimum topographic/exhumational conditions that lead to resolvable age perturbations? (ii) What is a promising sample strategy and where should we sample to maximize the resolution of palaeo-relief estimations? (iii) How can we efficiently correct AER? To answer the latter two questions we decompose topography into a finite set of sinusoidal functions using a Fast Fourier Transform (FFT) algorithm, and sum the resulting age perturbations of each function using the generated database. Compared to existing analytical and numerical approaches, this method enables a rapid estimation of theoretical age perturbations of large and complex landscapes.