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Bias in detrital fission track grain-age populations: Implications for reconstructing changing erosion rates

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A B S T R A C T

The sedimentary record is our principal archive of mass transfer across the Earth's surface in response to tectonic and climatic changes in the geologic past. The thermochronology of individual sediment grains (detrital thermochronology) has emerged as a critical tool to infer erosion rates and track mountain belt evolution. Such inferences are reliant upon the statistical inversion of detrital grain ages to unbiasedly approximate the cooling history of the source areas from which the sediment originated. However, it is challenging to critique the reliability and consistency of modelled ages. These arise both from fundamental measurement uncertainties and the assumptions we employ in inverting the data. For detrital fission track modelling of young detrital samples, this problem is particularly acute since the uncertainty on the track counts produces uncertainty in the age estimates. We apply Monte-Carlo modelling to generate synthetic detrital data conditioned on known closure age models, and then invert the grain data to assess the reliability of different inversion schemes. The results clearly demonstrate that existing practice can be subject to large uncertainty, to systematic bias and to non-uniqueness of interpretation. We then show how to map such regions of systematic bias in the population modelling as a function of the true closure ages, and how this bias propagates through into the lag-time modelling. Applying the method to real data from the Siwalik group sediments in western Nepal, we find no evidence for a change in the underlying climate or tectonic processes, since the apparent change in lag coincides with a thresholded change in the resolution of the population modelling. This paper shows how to map regions of systematic bias in the population modelling as a function of the true closure ages, and how this bias propagates through into the lag-time modelling and can be applied retrospectively to existing studies. However, it is equally applicable to other age inversion schemes such as minimum age modelling. The application of these methods will enhance current practice and facilitate more robust interpretation of grain ages, in particular in discriminating between stationary and non-stationary geological and climatic processes.

1. Introduction

The reconstruction of past erosion rates is critical in determining the evolution of past sediment fluxes (Allen et al., 2013), the development of active mountain ranges (Jamieson and Beaumont, 1989) and evolving surface topography (England and Molnar, 1990). Erosion records the interplay of climate, lithology and tectonics, and so past erosion rates are also commonly interpreted in terms of these controls. Methodologies for reconstructing erosion over millions of years are dominated by measurements of sediment volumes and measuring the cooling history of rocks (thermochronology) where cooling is used as a proxy for exhumation of rock through erosion (Reiners and Brandon, 2006).

Bedrock thermochronology analyses the cooling history of a number of crystals from a single rock sample where all the grains have experienced the same history. In order to reconstruct the cooling history of a bedrock sample, multiple thermochronometers that record the time of passage through a range of closure isotherms are required. For regional analyses, multiple samples have to be collected, ideally from a range of different elevations (e.g. Fitzgerald et al., 1995); spatial interpolation may then enable regional erosion histories to be reconstructed (e.g. Vernon et al., 2008). Bedrock thermochronology often misses the early, now substantially eroded part of the exhumation history.

An alternative to regional bedrock sampling is to analyse the sediment sourced from river catchments that drain the region

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over variable timescales; this approach is termed detrital thermochronology (Garver et al., 1999). In this method, grains originate from erosion of a source area that covers a broad region where exhumation rates are likely to vary, and hence the age distributions should record that variability. For sediment samples taken from the stratigraphic record, the age distributions record exhumation rates averaged over the time intervals for each grain to pass from its closure depth to the surface; these intervals will be different for the different populations. This ability to reconstruct ancient exhumation rates of the upper few kilometres of the crust for different stratigraphic time intervals using a single technique has increased understanding of the evolution of mountain chains such as the Alps (Bernet et al., 2009; Glotzbach et al., 2011) and the Himalaya (e.g. van der Beek et al., 2006).

A widely used thermochronometer is fission-track (FT) analysis of apatite and zircon grains (e.g., Gallagher et al., 1998; Tagami and O'Sullivan, 2005). In contrast to noble-gas based methods (e.g. Ar–Ar, (U–Th)/He), FT analysis is relatively insensitive to abrasion of grains during sediment transport and so is most suited to detrital thermochronology. In the simplest case, the FT method takes grains of apatite or zircon, measures the density of spontaneous fission tracks that have damaged the crystal lattice of the grain, and uses independent information of the amount of uranium in the grain to estimate a duration since the grain started accumulating tracks (Fleischer et al., 1975; Price and Walker, 1963). The detrital fission-track (DFT) method is similar to bedrock FT up to the point where individual grain ages are estimated. Since detrital samples contain grains from multiple bedrock sources that were exhuming at different rates, we cannot assume that a common pooled age is a useful measure for characterising the composite cooling histories recorded in the detrital sample.

There are two commonly applied methods used to analyse detrital grain age data. The first uses population modelling to invert samples with up to ~ 120 grains sampled from modern river sediments or the stratigraphic record to find a parsimonious set of population ages that explain the variance in the observed grain ages (Brandon, 1992, 2002; Galbraith, 1988; Galbraith and Green, 1990; Galbraith and Laslett, 1993). These populations, especially the youngest P_1 population, are then interpreted to make inferences about the evolution of regional erosion rates, as well as sediment provenance and catchment reorganisation (e.g., Bernet et al., 2001, 2009; Glotzbach et al., 2011; Kirstein et al., 2010). The second method uses one of several methods to invert for a minimum age consistent with the population of ages (e.g. Galbraith and Laslett, 1993; Galbraith, 2005).

This paper considers how the component age populations in detrital fission-track analysis are estimated, and how they relate to "true" closure ages experienced by the grains. We explore issues of bias, uniqueness, and uncertainty when identifying component populations within detrital samples. Monte-Carlo sampling is used to generate synthetic DFT samples where the underlying closure age distribution is specified and our ability to recover the known closure age(s) in multiple random samples is tested. In these samples, the only sources of uncertainty are the probabilistic assignment of closure ages to each grain and Poisson counting errors on the number of spontaneous tracks. We then apply these methods to facilitate a more robust reinterpretation of detrital data from the Siwaliks (van der Beek et al., 2006). The power of this computational method comes in the scale of the samples that can be analysed; we have typically run ~500,000 synthetic detrital samples which take ~2 days on a desktop computer. This allows us to critique previous interpretations of data in a transparent and systematic manner. Specifically, the method quantifies the emergence of artefacts as the resolution of population modelling degrades.

2. Fission track theory and age models

Fission tracks in crystals, such as apatite and zircon, are the record of lattice damage generated by the spontaneous decay of ^{238}U or the induced decay of ^{235}U. These tracks become visible under a microscope when the crystals are mounted, cut, polished and etched (Fleischer et al., 1975; Price and Walker, 1963). Annealing of the crystals removes fission tracks at a rate that increases with temperature; above some mineral-specific closure temperature all tracks are rapidly lost and below that temperature tracks accumulate. In un-reset samples, the spontaneous tracks provide a natural record of how many fission decays have occurred since cooling below the annealing temperature. In the external detector method (Gleadow, 1981), irradiation of the crystals induces ^{235}U to produce a set of induced tracks onto an external mica sheet from which the concentration of ^{235}U in the original crystal can be estimated. Since the isotopic ratio of $^{235}U/^{238}U$ is known, the induced track data can then be used to estimate the current concentration of ^{238}U in each crystal. Hence, independent knowledge of the amount of radioactive isotopes in a crystal and the measurement of the number of spontaneous tracks, which have only accumulated since cooling below the closure temperature, allows us to estimate how long the mineral has been below its closure temperature. These mineral-specific ages are known as grain ages and are calculated using the FT age equation (Price and Walker, 1963). When this equation is calibrated using the zeta method (Hurford and Green, 1983), the age estimate of the uth grain is given by:

$$\tau_u = \frac{1}{\lambda_{U^{238}}} \ln\left(1 + \frac{1}{2}\lambda_{U^{238}}\zeta\rho_d\frac{\rho_{s,u}}{\rho_{i,u}}\right) \tag{1}$$

where zeta, ζ, is an empirically determined analyst-specific constant estimated by dating samples of known age (Hurford and Green, 1983). Other terms are the U^{238} decay rate ($\lambda_{U^{238}} = 1.55125 \times 10^{-4}$ Ma^{-1}), the track density in the standard glass used to measure the neutron fluence (ρ_d) and the ratio of spontaneous to induced track densities ($\rho_{s,u}/\rho_{i,u}$). When measured over a fixed area, the density ratio can be estimated from the ratio of the number of tracks $N_{s,u}/N_{i,u}$.

Due to the effect of counting errors on $N_{s,u}$ and $N_{i,u}$, individual grain ages are often subject to large uncertainties. Hence, the motivation for studying samples composed of many grains is to enhance the statistical robustness by finding a set of age populations consistent with a statistically well sampled set of observed grain ages. This problem is more acute for detrital apatite fission-track analysis than for detrital zircon. The latter system is characterised by a higher closure temperature and generally higher U-content; thus both $N_{s,u}$ and $N_{i,u}$ will tend to be higher for zircon (e.g., Garver et al., 1999).

2.1. Inverse models for fission track ages

Inverse modelling refers to the numerical process by which information is obtained from a (detrital) FT sample with the intention of enabling an interpretation to be made regarding the cooling histories of the grains.

2.1.1. The pooled age

Where the Chi-squared test indicates low age dispersion, it can be assumed that all of the grains have experienced the same temperature history and hence the same true cooling age; this is commonly the case in bedrock samples. The maximum likelihood solution for the common pooled age is given by:

$$\tau_{pooled} = \frac{1}{\lambda_{U^{238}}} \ln\left(1 + \frac{1}{2}\lambda_{U^{238}}\zeta\rho_d\frac{N_{s,total}}{N_{i,total}}\right) \tag{2}$$