Supplementary Information 1

1. Palynological Analysis

Two samples were processed for palynological analysis following standard procedures (Traverse, 2007). Samples were digested using HCl and HF and then sieved using 10 μm and 100 μm mesh screens and mounted on glass. Light microscopy was used to examine the palynological content. Morphological features were compared with descriptions and illustrations from several sources (Dueñas, 1980; Germeraad et al., 1968; Gonzalez, 1967; Jaramillo & Dilcher, 2001; Jaramillo et al., 2007, 2010, 2011; Lorente, 1986; Muller et al., 1987; van der Hammen, 1956). Sections were dated using the palynological zonation proposed by Jaramillo et al. (2011); the palynostratigraphic zonation proposed by Lorente (1986) was also used.

2. Apatite Fission–Track Analyses

The 9 new analyses presented here were conducted at the Laboratory of Low Temperature Thermochronometry at the Universidade de São Paulo, Brasil. Apatite grains were concentrated following conventional heavy liquids and magnetic separation procedures. Apatite grains were then immersed in an epoxy resin and cured at ambient temperature for 24 h. After grinding and polishing to expose the internal surfaces, the apatites were etched with 5.5 HNO_3 for 20.0 s (±0.5 s) at 21 °C (±1 °C) to reveal spontaneous tracks. Analytical procedures followed the external detector method (Gleadow, 1981). All three detrital samples and bedrock samples SNT–16 and SNT–19 were irradiated at the Oregon State University TRIGA research reactor, with a total neutron fluence of 9×10^{15} n cm^{-2}. The remaining 4 bedrock samples were irradiated at the Universidade de São Paulo IEA–R1 nuclear reactor, with a neutron fluence of 3×10^{15} n cm^{-2}. Following irradiation, the induced tracks were etched with 40% hydrofluoric acid at 21 °C for 45 minutes. Fission–tracks were counted at the Universidade de São Paulo using 1250X magnification (dry objective) on an Olympus BX51 microscope with a drawing tube located above a digitizing tablet and a Kinetec ™ computer–controlled stage driven by the FTStage program (Dumitru, 1993). Ages and errors were calculated using the zeta calibration method (Hurford & Green, 1983) and are reported at the 2σ level. The zeta calibration factors used for age calculations were obtained for CN5 dosimetry glasses and were 351.7 ± 5.7 (samples Fundación and Cañas, Mauricio PARRA), 335.7 ± 6.6 (sample Guatapurí, Ana María PATIÑO), and 348.7 ± 7.3 (all other samples, Sebastián ECHEVERRI).

Complete bedrock AFT results are presented in Table 1 within the manuscript, single grain detrital AFT ages are presented in Tables 2–4 of the Supplementary Information S2, and the track length data are presented in Table 5 of the Supplementary Information S2.

3. (U–Th)/He Analytical Procedures

For (U–Th)/He dating, hand picking of approximately 30 inclusion–free and unfractured apatite grains from the Fundación, Guatapurí, and Cañas Rivers was performed at the LabTer IEE–USP under an Olympus SZX–16 binocular microscope equipped with a rotating tablet, polarized light, and a digital camera. The crystal dimensions necessary to model helium diffusion (Farley, 2002) were recorded, and each grain was then packed into a platinum tube.

At the University of Potsdam, Germany, the platinum tubes were loaded into a 25–spot laser chamber of an ASI Alphachron He extraction and analysis system equipped with a 30 W Coherent 978 nm diode laser and a Pfeiffer Prisma 200 Quadrupole mass spectrometer. Blank tubes and age standards were routinely analyzed together with unknown samples. The samples were heated by the laser system at 8 amps (ca. 3.5 W) for 5 minutes to release all He from the apatite grains. After exposure to a hot getter for 1 minute, which was designed to remove chemically active gas species, the gas released after heating was purified. The abundance of ^{4}He in the purified gas was measured by isotope dilution using a ^{3}He tracer calibrated against a manometrically determined ^{4}He standard. A second analysis or re–extraction was performed for each sample to ensure that the grain was completely degassed. Analysis of U, Th, and Sm were conducted at the clean lab at GFZ Potsdam by isotope dilution ICP–MS. The samples were placed in 3 ml Savillex PFA screw–cap vials, spiked with a HNO_3–based ^{235}U–^{230}Th spike and a HNO_3–based ^{149}Sm spike, and dissolved with ca. 0.5 ml 7N HNO_3. The spikes were calibrated against NIST–traceable certified reference material ICP concentration standards. To ensure the total sample dissolution and isotopic homogenization between the samples and the spikes, the vials were placed on a hotplate at ca. 100 °C for at least 24 h. The solution was then evaporated to dryness and redissolved for another 24 h in 1.5 ml 2% HNO_3. The solution was then analyzed for U, Th, and Sm isotopic compositions at GFZ Potsdam on a Thermo Element 2 XR ICP–MS equipped with a CETAC ASX–520 autosampler system and was run in low–resolution mode to maximize the transmission of ions. Urani-

um 234 was also analyzed to detect potential Pt–Ar isobaric interference on the U mass spectrum. Repeated analyses of the $^{149}Sm/^{147}Sm$ ratio and of the NIST SRM material U–500 were used to monitor instrumental mass fractionation. Age calculations followed the procedure of (Meesters & Dunai, 2005). A 1σ uncertainty is reported for all ages. The potential effect of radiation damage on AHe data was assessed by comparing the effective uranium (e[U] = U + 0.235*Th) with individual ages as a proxy for radiation damage following the model of (Flowers et al., 2009). Single aliquot data are presented in Table 6 of the Supplementary Information S2.

4. Log–likelihood Assumptions and Computations in Pecube

In this section, we explain the computation of the log–likelihood in Pecube for both bedrock and detrital data. We explain the main assumptions of the statistical model that lies in the background of the computation.

4.1. Notation

Pecube computes the heat distribution in a 3D cube, allowing changing topography. Rocks are advected and their temperature history allows the computation of a synthetic thermochronological age. Pecube uses a set of parameters that regulate the initial and boundary conditions and parameters included in the computation of the ages. We call the Pecube forward model for F, and the set of all the parameters for Q. A bedrock sample b_i^j is collected at a lateral location (x,y) on the topography for thermochronometer j. A detrital sample is similarly denoted by d_i^j. We omit the index j in the next explanation, which refers only to a specific thermochron.

4.2. The Error Model for Bedrock and Detrital Data

The bedrock sample b_i differs from a forward simulation of the bedrock age by a bedrock residual. This residual $\epsilon_b(x,y)$ depends on the lateral location. The residual is assumed to have a normal distribution with mean 0 and variance $\sigma_b^2(x,y)$. The residuals are independent from location to location (although we could have considered a variogram for lateral dependency, which is more realistic but also more complicated).

In mathematical terms, we modeled the bedrock data as:

$$b_i = F(x,y,Q) + \epsilon_b(x,y) \quad (1)$$

Similarly, using a detrital residual, we modeled the detrital data as:

$$d_i = F(x,y,Q) + \epsilon_d(x,y) \quad (2)$$

4.3. Maximum Likelihood Estimation

Our objective was to obtain an estimate of the parameters based on all the bedrock and detrital data. We use the classical MLE, or maximum likelihood estimation method.

From Equation (1), because the residuals are normally distributed, the probability of observing a bedrock data value b_i, given a known value of the parameter Q is:

$$p(b_i \mid Q) = \frac{1}{\sqrt{2\pi}} e^{-\frac{(b_i - F(x,y,Q))^2}{2\sigma_b^2(x,y)}} \quad (3)$$

We now assume that the samples are independent, so the joint probability of the sample is the product of the marginals:

$$p(b_1, b_2, ..., b_{N_b} \mid Q) = p(b_1 \mid Q)\, p(b_2 \mid Q) \ldots p(b_{N_b} \mid Q)$$

With this assumption, the log–likelihood of the full bedrock sample b is the logarithm of the joint probability of the sample, given as a sum of logarithms:

$$LLH(b,Q) = \sum_{i=1}^{N_b} \log(p(b_i \mid Q))$$

This definition says that LLH is proportional to the sum of the squared deviations from the samples, normalized with the standard deviation of the residuals:

$$LLH(b,Q) \sim -\sum_{i=1}^{N_b} \frac{(bi - F(x,y,Q))^2}{2\sigma_b^2(x,y)}$$

Note: In the case of a linear regression (in our case, we have a very nonlinear regression), maximizing the log–likelihood is equivalent to finding the OLS (ordinary least squares) estimator.

By maximizing LLH(b,Q) among the parameters Q, we obtain a parameter $\hat{Q}$ that maximizes the log–likelihood. This is the definition of MLE.

It remains to comment on the standard deviation of the residual. We have several choices:

1. The standard deviation is constant for all samples; in this case, LLH is simply the squared error, as $\sigma_b^2(x,y)$ is outside the sum.
2. The standard deviation depends only on the measurement error of each sample; in this case, LLH is closely related to the misfit in Pecube.
3. The standard deviation is proportional to the modeled age; in this case, the error structure changes laterally.
4. The standard deviation is the sum of both a proportion of the ages and the measurement error.

We have assumed that the standard deviation σ(x,y) is proportional to the modeled ages F(x,y,Q) only. We believe that this is a reasonable assumption given that the measured ages have an error proportional to the ages.

Therefore, our major assumption is as follows: *The error of the residual (the unknown part of our model) is laterally*

heterogeneous. This implies that there are lateral variations in the error that we model by a proportion of the forward ages.

Remarks

1. We have used the definition of the LLH directly (exponential and then the logarithm) to filter observations that are unlikely. This could have been done differently by simply summing the squared deviations, but this does not give a probabilistic view of the problem.
2. We did not implement a search for the optimum in the parameter space, we simply ran many models; the geologist may wish to limit the parameter range.
3. The factors or proportions of the ages for the residual are: 5%, 5%, 10%, 10%, and 4% for AHe, ZHe, AFT, ZFT, and Ar–Ar, respectively.

4.4. Detrital Data

For the detrital data, the definition of LLH is similar to that for bedrock, but in this case, the sum of the probabilities is also over the catchment. We have:

$$\mathrm{LLH}(d,Q) = \sum_{i=1}^{N_d} \log(p(d_i \mid Q))$$

The probability of a sample in the catchment depends on the origin of the sample. Let C denote the catchment. Let (x_i,y_i) denote the possible origin of the sample in the catchment. The full probability can be split as follows (known probability formula):

$$p(d_i \mid Q) = \sum_{(x_i,y_i) \text{ in } C} p(d_i \mid Q,x_i,y_i)\; p\,(x_i,y_i)$$

This is the assumption: the probability that the detrital sample was originally located at (x_i,y_i), denoted by $p(x_i,y_i)$, is proportional to the exhumation rate E(x,y). The more exhumation in a region of the catchment (and also denudation), the higher the probability that the sample comes from this location.

Thus, the LLH for detrital samples is defined as:

$$\mathrm{LLH}(d,Q) = \sum_{i=1}^{N_d} \sum_{(x_i,y_i) \text{ in } C} \log(d_i \mid Q, x_i,y_i)\; E(x_i,y_i)$$

The term $p(d_i \mid Q,x_i,y_i)$ is computed as in Equation (3), but we require the modeled age at the location of the catchment (x_i,y_i).

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