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Research Paper

Effect of density uncertainties in cosmogenic ^{10}Be depth-profiles: Dating a cemented Pleistocene alluvial fan (Carboneras Fault, SE Iberia)

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ABSTRACT

Cosmonuclide depth-profiles can be used to calculate both the age of landforms and the rates at which erosion has affected them since their formation. Results are heavily dependent on the selection of the appropriate density of the material exposed to cosmic radiation. In materials where density has changed significantly through time, as in alluvial sediments affected by post-depositional calcrete cementation, the uncertainties in density must be accurately modelled to produce reliable results. We develop new equations for an accurate account of density uncertainties and to test the effect of density gain due to cementation processes. We apply them to two ^{10}Be depth-profiles measured in an alluvial fan deformed by the Carboneras Fault (SE Iberia). When a linear increase of density through time is considered, model results yield an age ranging from 200 ka to 1 Ma within 1σ confidence level.

1. Introduction

Cosmonuclide exposure dating is a dependable technique in landscape evolution studies (Gosse and Phillips, 2001). The concentration of cosmonuclides (e.g. ^{10}Be) measured at the surface of a given landform depends, among other parameters, on the amount of cosmonuclide lost by erosion, and on the time of exposure to cosmic radiation. If erosion is assumed to be negligible for the period of exposure, an exposure age can be deduced from the cosmonuclide concentrations found in superficial materials (Lal, 1991). Moreover, where erosion is not negligible, it is possible to deduce an exposure age and an erosion rate using numerical modeling of cosmonuclide concentrations from a series of samples taken along a depth profile (Siame et al., 2004).

Advances in Accelerator Mass Spectrometry (AMS) in recent years have increased the precision in ^{10}Be concentration measurements. Thus, as a result of more precise measurements and the increased speed of computer processors there is now room for improvement in the conceptual models used to interpret concentration depth-profiles. Exposure ages and erosion rates for a given surface have been calculated in the literature by chi-square inverse modeling of the measured cosmonuclide concentration depth-profiles, assuming no variation of the material density (Siame et al., 2004; Braucher et al., 2009; Nissen et al., 2009). However, where post-depositional processes produce density variations through time (for example by calcrete formation), the assumption of constant density may produce significant age inaccuracies. A meticulous processing of density uncertainties and of density evolution is therefore necessary to obtain reliable chronological results from cosmonuclide depth-profile modeling.

The aims of this paper are (1) to assess the precision of age and erosion estimation for depth-profiles affected by density uncertainties, (2) to develop a model for ^{10}Be depth-profiles, taking into account the variations in sediment density through time, and (3) to apply the new model to constrain the age of the Pleistocene El Puntal fan (Carboneras Fault).

2. Modeling density variations and uncertainties in ^{10}Be depth-profiles

To numerically estimate the age and the erosion rate experienced at a depositional landform surface, Siame et al. (2004) and Braucher et al. (2009) used the chi-square inverse approach to fit synthetic ^{10}Be depth-profile models to measured ^{10}Be datasets,

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assuming no variation in the material density. In this work, we use the same approach but we introduce the modifications required to account for density variations through time. Moreover, we present a way of considering the density data as a gaussian distribution in the chi-square inverse approach.

2.1. Constant-density model

The ^{10}Be concentration (C) at a depth x (g cm^{-2}) from the top surface of a deposit, which has been eroding at a constant rate ε (g cm^{-2} a^{-1}) since its formation (t years ago), was described by Lal (1991) as:

$$\frac{\delta C}{\delta t} = Pe^{\frac{-x}{\Lambda}} + \varepsilon\frac{\delta C}{\delta x} - \lambda C \tag{1}$$

where P is the surface production rate in at g^{-1} a^{-1}, which can be calculated using the CRONUS-Earth online calculator (Balco et al., 2008), Λ is the attenuation length of the cosmic radiation (g cm^{-2}), and λ is the ^{10}Be decay constant (a^{-1}). Eq. (1) may be solved as:

$$C_{(x,\varepsilon,t)} = \frac{P}{\frac{\varepsilon}{\Lambda}+\lambda}e^{-\frac{x}{\Lambda}}\left(1-e^{-t\left(\lambda+\frac{\varepsilon}{\Lambda}\right)}\right) \tag{2}$$

Depth can also be expressed as $x = \rho\cdot z$, where z is the current profile depth in cm and ρ is the mean density of the rock or sediment in g cm^{-3}. Considering that the production of ^{10}Be is due to spallation, stopping muons and fast muons, which have different attenuation lengths and production rates, the ^{10}Be concentration can be expressed as:

$$\begin{aligned} C_{(C_{\text{Inher.}},x,\varepsilon,t)} = C_{\text{Inher.}} &+ \frac{P_{\text{spal.}}}{\frac{\varepsilon}{\Lambda_{\text{spal.}}}+\lambda}e^{-\frac{x}{\Lambda_{\text{spal.}}}}\left(1-e^{-t\left(\lambda+\frac{\varepsilon}{\Lambda_{\text{spal.}}}\right)}\right) \\ &+ \frac{P_{\text{stop}}}{\frac{\varepsilon}{\Lambda_{\text{stop}}}+\lambda}e^{-\frac{x}{\Lambda_{\text{stop}}}}\left(1-e^{-t\left(\lambda+\frac{\varepsilon}{\Lambda_{\text{stop}}}\right)}\right) \\ &+ \frac{P_{\text{fast}}}{\frac{\varepsilon}{\Lambda_{\text{fast}}}+\lambda}e^{-\frac{x}{\Lambda_{\text{fast}}}}\left(1-e^{-t\left(\lambda+\frac{\varepsilon}{\Lambda_{\text{fast}}}\right)}\right) \end{aligned} \tag{3}$$

where the first addend is the ^{10}Be inherited from the exposure of matter to cosmic rays before its deposition:

$$C_{\text{Inher.}} = C_{(x,0)}\cdot e^{-\lambda t} \tag{4}$$

In the case of alluvial fan deposits, this inherited ^{10}Be may be formed (1) during the deposition of the quartz grains in the source area, (2) during the exhumation of the source area, and (3) during the transportation of the quartz grains from the source area to the deposition site.

2.2. Variable-density model

If we consider that the density of the sediment decreases or increases constantly with time due to diagenetic processes, the ^{10}Be concentration can be described by:

$$\frac{\delta C}{\delta t} = Pe^{\frac{-x}{\Lambda}} + (\varepsilon + kx)\frac{\delta C}{\delta x} - \lambda C \tag{5}$$

where k is the rate of sediment density loss in g cm^{-3} a^{-1}. This factor can be expressed as:

$$k = \frac{\rho_0 - \rho_1}{t\rho_1} \tag{6}$$

where ρ_1 is the current density (g cm^{-3}), ρ_0 is the initial density and t is the age of the depositional surface in years. Therefore, negative values of k correspond to a constant-density gain. Eq. (5) can be solved as:

$$\begin{aligned} C_{(x,\varepsilon,t)} &= \frac{P}{k}\frac{e^{-\frac{\varepsilon}{k\Lambda}}}{k\Lambda}\left(\frac{(kx-\varepsilon)}{k\Lambda}\right)^{-\frac{\lambda}{k}}\Gamma\left[\frac{\lambda}{k},\frac{e^{-kt}(kx-\varepsilon)}{k\Lambda},\frac{(kx-\varepsilon)}{k\Lambda}\right] \\ &= \frac{P}{k}\frac{e^{-\frac{\varepsilon}{k\Lambda}}}{k\Lambda}\left(\frac{(kx-\varepsilon)}{k\Lambda}\right)^{-\frac{\lambda}{k}}\int_{\frac{e^{-kt}(kx-\varepsilon)}{k\Lambda}}^{\frac{(kx-\varepsilon)}{k\Lambda}} r^{\frac{\lambda}{k}-1}e^{-r}\mathrm{d}r \end{aligned} \tag{7}$$

Considering inheritance and production of ^{10}Be due to spallation, stopping muons and fast muons, the variable-density ^{10}Be concentration model will be:

$$\begin{aligned} C_{(C_{\text{Inher.}},x,\varepsilon,t)} = C_{\text{Inher.}} &+ \frac{P_{\text{spal.}}}{k}\frac{e^{-\frac{\varepsilon}{k\Lambda_{\text{spal.}}}}}{k\Lambda_{\text{spal.}}}\left(\frac{(kx-\varepsilon)}{k\Lambda_{\text{spal.}}}\right)^{-\frac{\lambda}{k}}\Gamma\left[\frac{\lambda}{k},\frac{e^{-kt}(kx-\varepsilon)}{k\Lambda_{\text{spal.}}},\frac{(kx-\varepsilon)}{k\Lambda_{\text{spal.}}}\right] \\ &+ \frac{P_{\text{stop}}}{k}\frac{e^{-\frac{\varepsilon}{k\Lambda_{\text{stop}}}}}{k\Lambda_{\text{stop}}}\left(\frac{(kx-\varepsilon)}{k\Lambda_{\text{stop}}}\right)^{-\frac{\lambda}{k}}\Gamma\left[\frac{\lambda}{k},\frac{e^{-kt}(kx-\varepsilon)}{k\Lambda_{\text{stop}}},\frac{(kx-\varepsilon)}{k\Lambda_{\text{stop}}}\right] \\ &+ \frac{P_{\text{fast}}}{k}\frac{e^{-\frac{\varepsilon}{k\Lambda_{\text{fast}}}}}{k\Lambda_{\text{fast}}}\left(\frac{(kx-\varepsilon)}{k\Lambda_{\text{fast}}}\right)^{-\frac{\lambda}{k}}\Gamma\left[\frac{\lambda}{k},\frac{e^{-kt}(kx-\varepsilon)}{k\Lambda_{\text{fast}}},\frac{(kx-\varepsilon)}{k\Lambda_{\text{fast}}}\right] \end{aligned} \tag{8}$$

2.2.1. χ^2 fit modeling

Depth-profile sampling provides a set of data of N ^{10}Be concentrations (C_i) measured in samples obtained from several profile depths (x_i). Numerical modeling was performed to calculate the time (t), inheritance ($C_{\text{Inher.}}$) and erosion rate (ε) values that fit the data obtained from the sampled profiles. To fit the models (Eqs. 3 and 8) into the data, it is necessary to compute them with an inverse method, especially if uncertainty boundaries need to be demarcated in the $C_{\text{Inher.}}$-ε-t space. We used the same χ^2 fit-based inverse method employed by Siame et al. (2004) or Braucher et al. (2009). This method defines the solution in the $C_{\text{Inher.}}$- ε-t space by minimizing the χ^2 value:

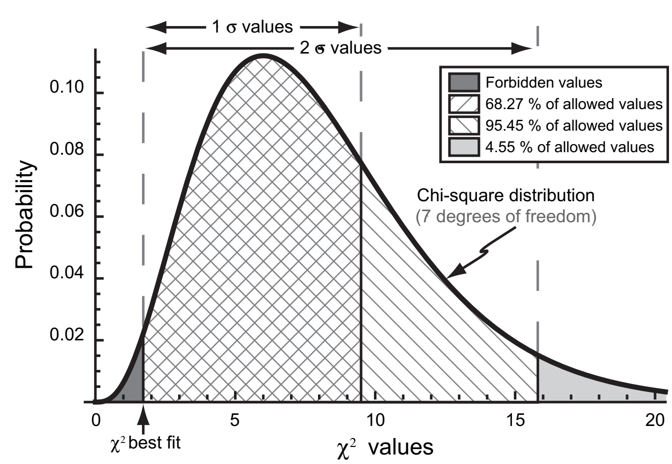

Fig. 1. Strategy followed to choose χ^2 values corresponding to 1σ and 2σ confidence levels over a chi-squared distribution. 1σ values vary from χ^2_{min} to a χ^2 value that restricts the distribution area to 68.27% of all possible distribution values (i.e. the part of the distribution beyond χ^2_{min}). 2σ values restrict the distribution area to 95.45% of allowed values.