Supplementary Material

**10Be cosmogenic nuclide dating pretreatment and calculation**

All samples were crushed into 600-850 μm and carbonate eliminated by HCl (10%) and repeatedly purified by HF: HNO3 solution until the Al concentration was lower than 100ppm. The purified quartz was spiked with a Be carrier and then dissolved with concentrated HF acid. Following anion and cation exchange in a series of column chromatography procedures, the sample solution was neutralized by NH4OH to precipitate Be(OH)2. The precipitations were oxidized to BeO in a furnace, then pressed into Cu target holders after Nb powder was added. The 10Be/9Be measurements were made in the 5MV AMS Lab in SUERC, the value of the 10Be/9Be blank yielded 1.60-2.64×10-14 and is 1-2 magnitude lower than those values of samples. Ratios were normalized to the standard NIST\_27900.

Under conditions of constant production rate and constant erosion rate, cosmogenic nuclide concentration of surface that is exposed at time *t* can be expressed as (Lal, 1991; Balco et al., 2008; Braucher et al., 2009)

(1)

where 𝑃𝑛,0, 𝑃𝑚1,0, and 𝑃𝑚2,0 are the surface production rate induced by nucleons, negative muons, and fast muons; 𝛬𝑛, 𝛬𝑚1, 𝑎𝑛𝑑 𝛬𝑚2 are the attenuation lengths of the nucleons and muons (negative and fast), respectively; *z* is the surface depth; 𝜆 is the decay constant, and *r* is a constant erosion rate. Based on equation 1, the production of cosmogenic nuclides may be simplified into two major components: the production rate at specific depth (*Pz*), and the effective exposure age of the site (*Te*), which is the time that is required to accumulate concentration *Nz* at production rate *Pz*without erosion and radioactive decay (Wang and Oskin, 2021):

(2a)

Where , , *i* = *n*, *m1*, *m2* (2a)

The 10Be concentration (*C*) measured from a suite of samples includes the in-situ produced concentration (*Nz*), and the inherited concentration (𝐶𝑖𝑛ℎ)

(3)

In realistic cases, estimate total eroded thickness (*D*) from field evidence could be more straightforward than to obtain an erosion rate. With eroded thickness, the effective age of each pathway may be rewritten as:

, *i* = *n*, *m1*, *m2* (4)

We rewrite the effective age related to muons (*Tem*) into a fraction (g) of the effective age related to nucleons (*Ten*), detailed derivation is referred to Wang and Oskin (2021) The fraction *g* can be approximated solely from knowledge of the eroded thickness (*D*):

, *i* =1, 2 (5)

Bring *gi* into equation 3:

(6)

Using equation 6, *Ten* and *Cinh* can be found by applying least squares linear regression with known production rates, eroded thickness, and sample concentrations. To estimate the exposure age, we need to find the solution for

(7)

t may be found in the derivative of equation 7 iteratively by applying the Newton’s method:

(8)

The exposure age can be iterated from

(9)

With initial *t0* = *Ten*

**Reference**

1. Balco, G., Stone, J. O., Lifton, N. A., and Dunai, T. J. (2008). A complete and easily accessible means of calculating surface exposure ages or erosion rates from 10Be and 26Al measurements. *Quaternary Geochronology* 3, 174–195. doi: 10.1016/j.quageo.2007.12.001.
2. Braucher, R., Del Castillo, P., Siame, L., Hidy, A. J., and Bourlés, D. L. (2009). Determination of both exposure time and denudation rate from an in situ-produced 10Be depth profile: A mathematical proof of uniqueness. Model sensitivity and applications to natural cases. *Quaternary Geochronology* 4, 56–67. doi: 10.1016/j.quageo.2008.06.001.
3. Lal, D. (1991). Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. *Earth and Planetary Science Letters* 104, 424–439. doi: 10.1016/0012-821X(91)90220-C.
4. Wang, Y., and Oskin, M. E. (2021). Combined linear regression and Monte Carlo approach to modelling exposure age depth profiles. *Geochronology Discussions*, 1–25.