Quaternary Geochronology 34 (2016) 75–80

Contents lists available at ScienceDirect

Quaternary Geochronology

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

Research paper

A test of the isochron burial dating method on fluvial gravels within the Pulu volcanic sequence, West Kunlun Mountains, China

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A R T I C L E   I N F O

Article history:
Received 26 December 2015
Received in revised form
15 April 2016
Accepted 26 April 2016
Available online 28 April 2016

Keywords:
Isochron burial dating
Intercomparison
Production rate ratio
Aluminum-26
Beryllium-10

A B S T R A C T

Isochron burial dating with cosmogenic nuclides is used in Quaternary geochronology for dating sediments in caves, terraces, basins, and other depositional environments. However, the method has seldom been rigorously tested against an independent chronology. Here, we report a direct comparison of isochron burial dating with K-Ar and $^{40}Ar/^{39}Ar$ bracketing ages on volcanic flows that sandwich a fluvial gravel layer in the Xinjiang province of northwestern China. The ages agree to within analytical uncertainty, validating the assumptions and physical constants used in the isochron burial dating method.

1. Introduction

Isochron burial dating with cosmogenic nuclides is an important tool for dating buried rocks, surfaces, and sediments. The method has been used for dating Plio-Pleistocene glaciation (Balco and Rovey, 2008, 2010), for dating sedimentary fill (Balco et al., 2013), for measuring long-term river incision and uplift rates (Erlanger et al., 2012; Darling et al., 2012; Çiner et al., 2015), and for dating archaeological and hominin fossil sites (Granger et al., 2015). Although the use of an isochron reduces uncertainty and improves the reliability of the burial dating method, there remain several important factors that can affect the age, especially including uncertainties in cosmogenic nuclide production rates and decay constants. It is therefore useful to compare isochron burial dating results with independent chronometers to validate the assumptions in the method.

The cosmogenic nuclide burial dating technique is based on the radioactive decay of cosmogenic nuclides in buried rocks that were once exposed at the surface. The method is most often based on ^{26}Al and ^{10}Be in the mineral quartz, because these two nuclides have a production rate ratio that is nearly constant and because quartz is common and exceptionally resistant to chemical weathering. The radioactive mean lives of ^{26}Al ($\tau_{26} = 1.021 \pm 0.024$ My; Nishiizumi, 2004) and ^{10}Be ($\tau_{10} = 2.005 \pm 0.017$ My; Chmeleff et al., 2010; Korschinek et al., 2010) are such that the burial dating method is applicable over the past ~5 million years.

Despite being used for many years, burial dating has seldom been compared to independent dating methods. This is because there are few other methods that are applicable to Plio-Pleistocene coarse clastic deposits, except where they are interbedded with volcanics or cave flowstones. In the cases where burial dating has been compared with other methods (e.g., Stock et al., 2005; Rovey et al., 2010; Gibbon et al., 2014; Çiner et al., 2015), the uncertainty in the burial ages due to measurement uncertainty is often sufficiently large that it is difficult to assess the validity of the assumptions in the burial dating method itself. It is also the case that the independent dating methods may not provide tight bracketing control on the deposit. In some cases, comparisons of burial dating with

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http://dx.doi.org/10.1016/j.quageo.2016.04.003
1871-1014/

independent chronologies has failed. Burial dating of amalgamated deposits has yielded ages that are too old due to reworking of the sediment from previously buried deposits (e.g., Hu et al., 2011; Wittmann et al., 2011; Matmon et al., 2012), violating an assumption of the method. Recently, the development of the isochron dating technique has allowed a way to identify reworking of individual clasts (Erlanger et al., 2012; Granger, 2014) and to correct for postburial production (Balco and Rovey, 2008), removing important sources of error in the burial dating method. Additionally, advances in accelerator mass spectrometry (AMS) techniques have led to dramatic improvements in the measurement of ^{26}Al (Granger et al., 2015). Here, we take advantage of these improvements to compare isochron burial dating with independent ages from ^{40}Ar/^{39}Ar in volcanic flows as an explicit test of the accuracy of the dating results.

Cosmogenic ^{26}Al and ^{10}Be in quartz that is exposed near the surface and then buried will follow Eq. (1).

$$N_{26} = N_{26,inh}\, e^{(-t/\tau_{26})} + \int P_{26,pb}(t')e^{(-t'/\tau_{26})}dt' \quad (1a)$$

$$N_{10} = N_{10,inh}\, e^{(-t/\tau_{10})} + \int P_{10,pb}(t')e^{(-t'/\tau_{10})}dt' \quad (1b)$$

where the numeric subscript indicates either ^{26}Al or ^{10}Be, the subscript *inh* indicates inheritance prior to burial, *t* represents time since burial, and the integral indicates the total production since burial due to a time-varying postburial production rate P_{pb} and t' is a dummy variable of integration.

There are two simplified approaches to solving the set of equations above. The first is to limit burial dating to samples for which postburial production is so small that it can safely be ignored. This approach, referred to here as simple burial dating, works for samples that begin with a high concentration of inherited nuclides and are then buried very deeply (10's to 100's of meters) and very quickly so that postburial production is small. Simple burial dating is often applied to cave deposits that are shielded deep beneath a bedrock roof. Simple burial dating has some limitations. Most importantly, with a single sample it is not possible to tell if the sample has experienced more than one burial episode. If sediment was buried once, for example in a cave or in a river terrace, and was then remobilized and buried again, the simple burial age will reflect a combination of the two burial episodes. The simple burial dating method also relies on complete shielding. Although postburial production can in some cases be accounted for using theoretical production rate profiles (e.g., Gibbon et al., 2014), the amount of postburial production is model-dependent and difficult to verify.

The isochron burial dating method was developed to avoid some of the restrictions of simple burial dating. In isochron burial dating multiple samples of the same burial age but with differing inherited concentrations are analyzed independently. In this case, the integrals representing postburial production in Eq. (1) can be treated as a constant (C_{26} and C_{10}) among all of the samples.

$$N_{26} = N_{26,inh}\, e^{(-t/\tau_{26})} + C_{26} \quad (2a)$$

$$N_{10} = N_{10,inh}\, e^{(-t/\tau_{10})} + C_{10} \quad (2b)$$

Eq. (2) can be combined into a single expression that relates N_{26} to N_{10}.

$$N_{26} = (N_{10} - C_{10})R_{inh}\, e^{(-t/\tau_{bur})} + C_{26} \quad (3)$$

where

$$R_{inh} = N_{26,inh}/N_{10,inh} \quad (4)$$

and

$$\tau_{bur} = 1/(1/\tau_{26} - 1/\tau_{10}) = 2.08 \pm 0.10 \text{ My} \quad (5)$$

Eq. (3) can be solved for a suite of samples, by modeling the inherited cosmogenic nuclide ratio (R_{inh}) and the relationship between C_{26} and C_{10}. When dating fluvial gravel deposits it is generally assumed that each sample represents a different erosion rate in the sediment source area (Erlanger et al., 2012). In this case, for steady erosion the inherited concentrations will be approximated by the following equations.

$$N_{26,inh} = \Sigma\{P_{26,i}/(1/\tau_{26} + E/Li)\} \quad (6a)$$

$$N_{10,inh} = \Sigma\{P_{10,i}/(1/\tau_{10} + E/Li)\} \quad (6b)$$

where the summation over the subscript *i* represents a multi-exponential approximation to the depth-dependent production rates by neutrons and muons (see Granger and Muzikar, 2001; Granger, 2014), *E* is erosion rate and L_i is a penetration length constant for cosmogenic nuclide production.

Substituting Eq. (6) into Eq. (2) yields Eq. (7).

$$N_{26} = (N_{10} - C_{10})\Sigma(P_{26,i}/P_{10,i}) \times [(1/\tau_{10} + E/Li)/(1/\tau_{26} + E/Li)]e^{(-t/\tau_{bur})} + C_{26} \quad (7)$$

In Eq. (7) the summation includes the production rate ratio ($P_{26,i}/P_{10,i}$). Here we assume that the production rate ratio is fixed at a value of 6.8 for production by both neutrons and muons and is thus invariant with depth. A model in which the production rate ratio increases with depth, as suggested for example by a muon production rate ratio of 8.3 determined by Braucher et al. (2013), could be calculated but would only be relevant for very high erosion rates. Because production rates by muons remain an active area of research, we ignore that complication here.

For samples with significant postburial production, a unique age determination also requires modeling the relationship between C_{26} and C_{10}. There are two endmember possibilities that are generally considered. The first is that a sample has been buried deeply for its entire history, but was suddenly exposed for an unknown period of time. This might be the case, for example, for a deep sedimentary deposit that has been exposed by a landslide or river cutbank failure of unknown age. In this case the concentrations simply reflect the production rate ratios, as indicated in Eq. (8).

$$C_{26} = \left(P_{26,pb}/P_{10,pb}\right)C_{10} \quad (8)$$

The second endmember case is for a sample that has been buried at a constant depth for its entire history. In this case the postburial cosmogenic nuclide buildup will reflect continued production and decay, as expressed in Eq. (9).

$$C_{26} = \left(P_{26,pb}/P_{10,pb}\right)(\tau_{26}/\tau_{10})\left[1 - e^{(-t/\tau_{26})}\right] / \left[1 - e^{(-t/\tau_{10})}\right]C_{10} \quad (9)$$

An isochron burial age requires simultaneously solving Eq. (7) and Eq. (8) or (9), depending on whether the site was recently exposed or has been continuously buried. The equations are normally solved by iteration (Balco and Rovey, 2008; Granger, 2014).

Although the isochron burial dating method is relatively straightforward, it requires knowledge about the relative