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

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Abstract

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 ⁴⁰Ar/³⁹Ar 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.

Keywords

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

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; Ciner 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 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 $^{40}\text{Ar}/^{39}\text{Ar}$ 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 equations (1).

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

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

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 equation (1) can be treated as a constant (C_{26} and C_{10}) among all of the samples.

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

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

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

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

where

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

and

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

Equation (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.

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

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

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).

Substituting equations (6) into equations (2) yields equation (7).

$$N_{26} = (N_{10} - C_{10}) \sum (P_{26,i}/P_{10,i}) [(1/\tau_{10} + E/L_i)/(1/\tau_{26} + E/L_i)] \exp(-t/\tau_{bur}) + C_{26} \quad (7)$$

In equation (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 equation (8).

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

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 equation (9).

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

An isochron burial age requires simultaneously solving equation (7) and equation (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 production rates and meanlives of ^{26}Al and ^{10}Be . It assumes that the production rate ratio (P_{26}/P_{10}) is constant both as a function of depth and for each sample. A potential source of uncertainty is that the production rate ratio may vary several percent as a function of elevation (Argento et al., 2015). Moreover, the exact production rate ratio remains debated, with values ranging from ~ 6.6 to ~ 7.3 (Lifton et al., 2015; Borchers et al., 2016). One way to test whether the isochron method yields accurate results is to compare results against an independent chronology.

Here we report results from a fluvial conglomerate that is sandwiched between two well-dated volcanic flows at Pulu, Xinjiang, northwest China. This is a nearly ideal place to directly compare isochron burial dating with K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$.

2. Geologic setting

The Pulu section is located within the piedmont of the western Kunlun Mountains, which form a high topographic boundary at the northern margin of the Tibetan Plateau where it meets the Tarim Basin (Fig. 1). Giant alluvial fans have developed along the mountain front where multiple rivers flow out of the deeply incised gorges that dissect the mountain range. The coarse grained fan sediments, known as the Xiyu conglomerate or Xiyu Formation, are Late Pliocene to early Quaternary deposits (~ 3.6 – 1.6 My) dated by magnetostratigraphy (Teng et al., 1996; Zheng et al., 2000). Fine grained aeolian deposits sourced from the Tarim Basin mantle the fan surfaces. A detailed description of regional geology has been documented by Wang et al. (2003).

The Xiyu conglomerate is locally capped by a series of volcanic flows along the Keriya River, one of the major rivers that discharges from the Kunlun Mountain (Fig. 1). The volcanics are exposed where the Keriya River has incised into the alluvial fans. The volcanic layers are present on both sides of the river at the same elevation, indicating that the lava flow spread across the valley prior to incision of the Keriya River (Liu, 1989). The volcanic rocks are trachyandesite and alkali basalt (Zhang et al., 2008).

Fig. 1.

The best outcrop of the volcanic flows and the conglomerate is found on the left bank of the river (Fig. 2a). At this section, the lower volcanic layer is 12-13 m thick, overlying the Xiyu conglomerate with a baked basal contact. Its bottom consists of volcanic agglomerate and its body is compact lava. The upper volcanic layer is about 30 m thick, and can be divided into three parts: volcanic agglomerate, compact lava and vesicular lava from bottom to top. The fluvial gravel embedded between the two volcanic flows is about 10-12 m thick, with its lower part dominated by coarse-grained granite, marble and quartzite pebbles with granite boulders, while its upper part is finer and composed of pebbles and sand (Fig. 2b; Wang et al., 2003).

Fig. 2.

The lower and upper volcanic flows were initially dated to 1.43 ± 0.03 My and 1.21 ± 0.02 My respectively using the K-Ar method (Liu, 1989). Later, ^{40}Ar - ^{39}Ar dating using stepwise heating on the bulk samples (with olivine and magnetite grains removed) shows the plateau age of the lower layer is 1.41 ± 0.04 My, and that of the upper layer is 1.20 ± 0.05 My (Li, 2008), consistent with the earlier results. Paleomagnetic measurements indicate that the primary magnetization of the upper layer is reversed, and that the paleo-latitude of the Pulu area was situated at 33.6°N when the eruption occurred (Meng et al., 1997), identical to today's latitude. The age is further constrained by an 80 m thick loess deposit that covers the upper volcanic

layer. The Brunhes/Matuyama boundary is found about 5 meters above the bottom of loess in a nearby section (Fang et al., 2001), placing a minimum age on the basalt that is consistent with the radiometric results.

We collected 8 quartzite or quartz-rich cobbles for ^{26}Al and ^{10}Be analysis from the gravel bed (2 m above its bottom) sandwiched between the two volcanic layers. The gravels contain cosmogenic nuclides that were inherited from exposure to secondary cosmic rays in their source area in the Kunlun Mountains, as well as any that accumulated as they were transported and then laid down by the Keriya River over the lower volcanic flow. Post-burial production would have occurred during continued deposition of the gravel, decreasing rapidly when the gravel was capped by the upper volcanic flow. Further postburial production would have occurred as the Keriya River incised and re-exposed the gravel bed in a steep cliff alongside the river. The cliff has retreated due to collapse, and an aeolian deposit now skirts its base. Recent quarry work has removed the aeolian cover, exposing the gravel bed.

3. Methods

The gravel clasts were crushed separately and quartz grains were extracted from each clast using magnetic separation, heavy liquids, and selective dissolution. The purified quartz samples were dissolved in hydrofluoric and nitric acids with the addition of a beryllium carrier solution. After evaporation of fluorides, Al and Be were extracted following standard methods at PRIME Lab using ion exchange chromatography in oxalic acid. Beryllium nitrate and aluminum chloride were decomposed by flame, and BeO and $\alpha\text{-Al}_2\text{O}_3$ were mixed with niobium powder. The pressed targets were measured by AMS at PRIME Lab, Purdue University against standards prepared by Nishiizumi (Nishiizumi, 2004; Nishiizumi et al., 2007). Aluminum was injected into the AMS as the molecular ion AlO^+ , and measured using the gas-filled-magnet to eliminate isobaric interference from MgO^+ . The use of a gas-filled-magnet greatly improves the aluminum beam current and measurement precision.

An isochron is constructed for the data assuming that each clast is derived from a source area eroding at steady-state (equation 7). The data are normalized for a source-area production rate corresponding to 36°N , 81.5°E , and an elevation of 4 km. It is impossible to identify with certainty the elevation at which any

individual clast was exposed prior to deposition at the site due to the exceptionally high relief in the watershed, so we chose a representative elevation between the highest peak elevation of ~6 km and the sampling elevation of ~2.5 km. We model production rates using the time-dependent scaling of Lifton et al. (2014) that accounts for variations in production rates due to changes in the geomagnetic field strength. We average the production rates over a period of 100,000 years prior to burial, and solve for the burial time and production rate by iteration. Because of uncertainties in the geomagnetic field reconstruction, we model uncertainties in the production rate as the standard deviation of production rates over the 100,000 year averaging window. We assume a production rate ratio $P_{26}/P_{10} = 6.8$ that is invariant with elevation. We modeled postburial production as recent exposure (equation 8). Uncertainties are determined using a Monte-Carlo method, with 10,000 repetitions in which ^{26}Al and ^{10}Be concentrations are varied about their mean according to a Gaussian distribution, and in which production rates are varied according to their standard deviation in the scaling model of Lifton et al. (2014). For each repetition the best-fit age, postburial concentrations, and source area production rates are determined by iteration. The regression is performed using the linear regression method of York et al. (2004) on data that have been transformed to a line to correct for nonlinearities due to the pre-depositional erosion rate, following equation (7). Parameters from the linear regression are then back-transformed to the original form of equations (7).

4. Results

Cosmogenic nuclide concentrations are given in Table 1. They cover a wide range of concentrations which improves the isochron determination. Measured ^{10}Be concentrations range from ~12,000 to 250,000 atoms per gram of quartz, while ^{26}Al concentrations range from ~67,000 to 870,000 atoms per gram. The data are shown in graphical form as ^{26}Al versus ^{10}Be in Fig. 3, together with the best-fit isochron.

Table 1

The isochron yields a burial age of 1.38 ± 0.07 My and a postburial ^{10}Be concentration of $10.8 \pm 1.7 \times 10^3$ at/g. Postburial production is equivalent to about 3000 years of exposure in a vertical cliff face, which is

plausible at this site. The modeled ^{10}Be production rate in the source area at the time of deposition is 55 ± 8 at/g/yr.

Fig. 3.

5. Discussion

There are two main conclusions that can be drawn from this comparison. The first is that the isochron method works, and that it gives the correct age even when there is demonstrable postburial production. The strength of the method can be illustrated by comparing the isochron result to those we would have obtained using simple burial dating. Table 1 shows the simple burial age results for each sample calculated independently without postburial production correction. The inferred minimum burial age varies systematically with cosmogenic nuclide concentration. Samples with low concentrations have burial ages that are far too young, while those with high concentrations approach the true age of the deposit. This is because samples with low concentrations have a higher proportion of their cosmogenic nuclide concentrations that is attributable to postburial production. Clearly, caution must be used when interpreting simple burial ages, especially in cases where the postburial production history is not well constrained.

The second conclusion is that the physical constants used in the calculation are unlikely to be far off from the true values. The most important uncertainties are in the radioactive mean lives of ^{26}Al and ^{10}Be , and in the production rate ratio (P_{26}/P_{10}). For ^{26}Al and ^{10}Be the combined uncertainties in their radioactive mean lives yields an effective uncertainty in the burial meanlife (τ_{bur}) of 5%, which propagates to a ~5% uncertainty in the burial age. For this site the systematic uncertainty due to uncertainty in the radioactive meanlives would be 0.07 My, comparable to the uncertainty in the regression. There is a larger uncertainty in the production rate ratio (P_{26}/P_{10}). The most recent production rate calibration study reported by Borchers et al. (2016) indicates a P_{26}/P_{10} ratio of 7.28 ± 0.80 at sea-level and high-latitude (SLHL). On the other hand, at individual sites at which both ^{26}Al and ^{10}Be were measured within that study, the measurements indicate a production rate ratio of 6.65 ± 0.62 (mean $\pm$ standard deviation). The reported discrepancy in production

rates is because the model of Borchers et al. (2016) includes nuclide-specific scaling in which the production rate ratio varies as a function of altitude and cutoff rigidity. In either case the production rate ratio itself has a stated uncertainty of $\sim 10\%$. The production rate ratio at our site calculated using the nuclide-specific scaling model (SA) in the CRONUS Earth Web Calculator of Marrero et al. (2016) ranges from 6.96 at an elevation of 2500 m to 6.72 at 6000 m, with a ratio of 6.85 at 4000 m. Our isochron model uses a production rate ratio of 6.8 that is invariant with altitude and achieves the correct age result.

It is possible to use the age constraints from the bracketing volcanic flows to evaluate the permissible range of P_{26}/P_{10} given the uncertainties in τ_{bur} . Fig. 4 shows the probability that our isochron age agrees with the known age of the gravel calculated as a function of P_{26}/P_{10} and τ_{bur} . The graph shows a best-fit interval from 6.3-6.9, with a 67% confidence interval that spans a production rate ratio from 6.0-7.2, and a 90% confidence interval from approximately 5.8-7.4. It is important to note that the values used in our calculations not only yielded the correct result but one that fits with the stratigraphic position near the bottom of the gravel. We suggest that the production rate ratio at the site should be constrained to $6.8^{+0.4}_{-0.8}$. A better determination of the production rate ratio would require more tightly bracketed burial ages and/or multiple intercomparison sites.

Fig. 4.

6. Conclusions

This test of the isochron burial dating method underscores the accuracy and reliability of the method, especially for sites with a poorly constrained history of postburial cosmogenic nuclide production. The modeled burial age of the gravel layer, 1.38 ± 0.07 My, closely matches the bracketing ages provided by dated volcanic flows of 1.20 ± 0.05 and 1.41 ± 0.04 My. The uncertainty in the burial age due to measurement error and the regression itself is 0.07 My, or 5%. Including systematic uncertainty in radioactive meanlives increases the uncertainty to 0.10 My, or 7%. The permissible production rate ratio P_{26}/P_{10} at the site is

bracketed to $6.8^{+0.4}_{-0.8}$ at 67% confidence, consistent with our assumption of 6.8 and also with the site-specific ratio of 6.72-6.96 calculated using the CRONUS Earth Web Calculator (Marrero et al., 2016). It remains important to better constrain the production rate ratio, both by measurement of samples at the surface today, and also by further comparisons between isochron burial dates and independent dating methods at other sites.

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Captions

Fig. 1. Location of the sampling site at Pulu in Xinjiang, northwest China. Uplifted fanglomerates at the southern end of the Tarim Basin north of the Kunlun Mountains have been incised by the Keriya River, exposing the capping volcanic flows shown in Fig. 2.

Fig. 2. Volcanic layers capping the Xiyu conglomerate near Pulu. (A) The Keriya river exposes the Xiyu conglomerate ①, capped by the lower ② (12-13 m) and upper ④ (~30 m) volcanic layers with a gravel layer ③ (10-12 m) sandwiched between them. The section is capped by loess ⑤ and the incised slopes are blanketed by eolian dust. (B) The gravel layer sampled for isochron burial dating, bracketed by the dated volcanic flows.

Fig. 3. Burial dating isochron for gravels sampled in this study. Each data point represents measurements of an individual clast, with the ellipses representing 1- σ analytical uncertainty. The best-fit isochron indicates an age of 1.38 ± 0.07 My. The line represents the recent exposure model for postburial production with the gray shading indicating the 1- σ uncertainty envelope. A line showing the production rate ratio ($P_{26}/P_{10} = 6.8$) is given for comparison.

Fig. 4. Probability that the isochron age matches the bounding ages of the volcanic flows, calculated as a function of the production rate ratio (P_{26}/P_{10}) and the burial meanlife (τ_{bur}).

Table 1 Nuclide concentrations of eight individual pebbles. The simple burial age of each clast is calculated (without postburial production corrections) following the method of Granger and Muzikar (2001). * Please note here the simple burial ages are for comparison only, not the true burial age.

SAMPLE ID	[¹⁰ Be] (10 ³ atoms/g)	[²⁶ Al] (10 ³ atoms/g)	²⁶ Al/ ¹⁰ Be Ratio	Simple Burial Age (My)*
PL11-2-8	12.11 ± 1.08	75.35 ± 3.10	6.22 ± 0.61	0.19 (+0.21/-0.22)
PL11-2-12	13.84 ± 0.81	83.75 ± 3.47	6.05 ± 0.44	0.23 (+0.19/-0.12)
PL11-2-7	35.43 ± 1.28	192.01 ± 5.62	5.42 ± 0.25	0.47 (+0.14/-0.07)
PL11-2-5	40.23 ± 2.41	190.34 ± 5.77	4.73 ± 0.32	0.77 (+0.18/-0.11)
PL11-2-6	42.97 ± 1.98	185.33 ± 8.81	4.31 ± 0.29	0.97 (+0.18/-0.11)
PL11-2-3	91.54 ± 2.52	381.84 ± 13.44	4.17 ± 0.19	1.04 (+0.13/-0.06)
PL11-2-11	189.94 ± 3.94	688.84 ± 12.70	3.63 ± 0.10	1.34 (+0.09/-0.02)
PL11-2-1	249.59 ± 7.78	831.38 ± 22.16	3.33 ± 0.14	1.53 (+0.13/-0.05)

figure 1

figure 2

figure 3

figure 4