继承性宇生核素对暴露测年结果影响的定量分析方法探讨

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内容提要: 宇生核素暴露测年过程中,通常假设在样品最后一次暴露前,样品中的宇生核素(继承性宇生核素)浓度为0。然而,大量的测年数据研究发现,样品的暴露年代结果会受到继承性核素的影响从而高估地貌的真实年代。因此,如何降低继承性核素对暴露年代结果的影响或者定量分析继承性核素的影响程度不仅可为地貌演化提供准确的年代数据,而且对宇生核素暴露测年技术的研究具有重要意义。因此,本文以宇生核素暴露测年技术在冰川地貌中应用为例,通过分析继承性核素的研究概况,并结合宇生核素暴露测年原理,探讨继承性核素对测年结果影响的定量分析方法。研究结果表明: ① 通过样品中 $n(^{26}Al)/n(^{10}Be)$ 值[即同一样品中宇生核素 Al^{26} 与 Be^{10} 浓度(单位为 atom/g)的比值]以及同一地貌位置多个的样品年代数据分布情况可初步判断测年结果是否受到继承性核素的影响;② 通过现代冰川冰碛物中宇生核素的浓度可以定量分析继承性核素对暴露测年结果的影响; ③ 通过计算冰碛垄顶部和一定深度(>2~3 m)样品的宇生核素浓度差,可以减少继承性核素的影响。本研究内容对冰川地貌宇生核素暴露测年具有重要意义。

关键词:继承性宇生核素;冰川地貌;TCN 暴露测年;定量分析

20世纪80年代以来,随着加速器质谱(accelerator mass spectrometry—AMS)测量技术的发展,原地生成宇宙成因核素(宇生核素)(In situ terrestrial cosmogenic nuclide, TCN)暴露测年技术受到年代学家的青睐,尤其是^{10}Be 和^{26}Al 两种核素应用最为广泛(Lal, 1991; Gosse and Phillips, 2001; Balco, 2011;吕延武等,2019)。该技术广泛应用于冰川地貌年代学研究(Dyke et al., 2002; 周尚哲和李吉均, 2003; Li Yingkui et al., 2011; Wang Jie et al., 2013),为全球第四纪冰川演化提供了数据支撑(Balco, 2011; Owen and Dortch, 2014; Zhang Mengyuan et al., 2018)。

然而随着大量测年数据的发表,冰川地貌 TCN 暴露测年存在的问题(由于继承性核素的影响造成的高估和冰川地貌后期受到侵蚀而造成的低估)也逐渐凸显(Hallet and Putkonen, 1994; Applegate et al., 2010, 2012; Balco, 2011; Owen and Dortch, 2014)。随着对冰川地貌年代数据精度和准确度要求的提高,有必要对影响暴露测年结果的因素进行研究。相关学者曾探讨过青藏高原地区宇生核素暴露测年数据存在的问题(基于数据统计和数学分析方法,侧重于说明冰碛垄行程后期受到侵蚀,其表面漂砾暴露年代数据分散)(Heyman et al., 2011a;张志刚等,2014)、利用冰碛垄表面碎屑物质测定相对较老的冰碛垄形成年代(张志刚等,2017)以及样品暴露时间尺度对利用宇生核素暴露测年技术估算最大侵蚀速率时的影响(张志刚等,2013)。然而,近年来,关于 TCN 暴露测年研究中继承性核素是否对

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暴露测年结果有影响? 影响是否可以忽略? 这一问题引起了大量冰川学家和年代学家的关注和争论(Makos et al., 2013; Dyke et al., 2014; Rades et al., 2015; Blomdin et al., 2016; Ciner et al., 2017)。在 TCN 暴露测年研究中,通常是假设样品在最后一次暴露之前没有携带残留的宇生核素,也就是在最后一次暴露之前没有继承性的宇生核素。如何判断冰川地貌 TCN 年代数据是否受到继承性核素的影响? 如果有影响,其影响程度有多大? 如何定量?

因此,基于上述问题,本文梳理了先前发表的第四纪冰川地貌测年研究中关于宇生核素继承性研究的文献,基于 TCN 暴露测年原理,尝试定量分析继承性核素对 TCN 暴露测年结果的影响。藉此希望为 TCN 暴露测年技术测定冰川地貌年代以及建立更加准确的年代学框架提供新的参考与借鉴。

1　TCN 暴露测年简介

1.1　基本原理

宇宙成因核素是由于宇宙射线粒子轰击地表岩石后发生核反应而生成的一系列稳定的或者放射性的新核素。根据发生反应中目标原子的位置(大气圈或岩石圈)可以分为大气宇宙成因核素和原地生成宇宙成因核素。现已发现的宇宙成因核素有 50 余种,在地表岩石样品中有 20 多种,其中最常用的有 4 种放射性核素(^{14}C、^{10}Be、^{26}Al 和 ^{36}Cl)和 2 种稳定核素(^{3}He 和 ^{21}Ne)(Gosse and Phillips, 2001)。宇生核素暴露测年方法是基于地表岩石中积累的宇生核素浓度与其暴露时间相关的一种测年手段(Lal, 1991)。

1.2　公式推导

由于地表岩石对宇宙射线具有吸收和阻挡作用,这样会导致宇生核素的生成速率随着采样深度而发生变化,在近地表几米的范围内,宇生核素 ^{10}Be 和 ^{26}Al 的生成速率按地表生成速率 $p(0)$ 呈指数递减形式。对于密度为 ρ(g/cm^3)的样品在其深度 x(cm)处的生成速率 $p(x)$ 为(Lal, 1991):

$$p(x)=p(0)\ \mathrm{e}^{-\rho x/\Lambda}=p(0)\ \mathrm{e}^{-\mu x} \tag{1}$$

式中:$p(x)$ 指地表以下深度 x(cm)处宇生核素的生成速率[atoms/(g・a)];$p(0)$ 指地表(深度为 0 cm)处的宇生核素生成速率;Λ 指目标岩石中原子核相互作用粒子的衰减路径长度(160 g/cm^2)(Brown et al., 1991),$\mu=\rho/\Lambda$ 为目标原子的吸收系数(cm^{-1})。

宇生核素暴露年代的基本原理是地表岩石中宇生核素浓度是地貌体暴露时间以及地貌体所受侵蚀速率的函数。根据相关假设可以推导出最小暴露年代和最大侵蚀速率。其主要推导过程如下(Lal, 1991):

$$\mathrm{d}N(x,t)/\mathrm{d}t=-N(x,t)\lambda+p(x,t) \tag{2}$$

由(1)知:$p(x,t)=p(0,t)\mathrm{e}^{-\mu x(t)}$　　(3)

公式(2)和(3)包含了一个假设:那就是宇生核素是由宇宙射线中子轰击产生的,而且其产生量随深度完全按指数递减。如果核素由介子和放射性反应而产生,则吸收衰减长度将随深度变化,$x(t)$ 的值由侵蚀速率 $\varepsilon(t)$ 定义:

$$x(t)=\int_0^t \varepsilon(t)\ \mathrm{d}t+c \tag{4}$$

当 $\varepsilon(t)=C$(常数),并假设宇宙射线强度为常量,即 $p(x,t)=p(x)$,则根据公式(2)、(3)和(4)通过解一阶线性方程可以求出关于浓度的函数关系式:

$$N(x,t)=N(x,0)\mathrm{e}^{-\lambda t}+\frac{p(0)}{\lambda+\mu\varepsilon}\mathrm{e}^{-\mu x}\left[1-\mathrm{e}^{-(\lambda+\mu\varepsilon)t}\right] \tag{5}$$

式中:$N(x,t)$ 指经过 t 时间后在 x 深度处样品的宇生核素浓度(atom/g);$N(x,0)$ 为暴露前深度 x 处样品的继承性宇生核素浓度(atom/g);$\lambda=\frac{\ln 2}{T}$(T 为半衰期)为放射性宇生核素的衰变系数(1/Ma);t 为暴露时间(a);ε 为侵蚀速率(cm/a)。

通常在计算过程中假设地表岩石初始宇生核素的浓度为 0,且宇宙射线通量为常数,地表宇生核素的产生速率为常数,因此,公式(5)可以简化为:

$$N=\frac{p}{\lambda+\mu\varepsilon}\left[1-\mathrm{e}^{-(\lambda+\mu\varepsilon)t}\right] \tag{6}$$

当假设地表没有受到风化—侵蚀,即侵蚀速率为 0,此时可以计算出的暴露年代为最小暴露年代:

$$t=-\frac{1}{\lambda}\ln\left[1-\frac{N\cdot\lambda}{p}\right] \tag{7}$$

1.3　单核素的应用

单核素暴露年代测定中,最常用的是 ^{10}Be,其应用情况也是建立在比较理想情况下,即假设地貌体在接受次级宇宙射线粒子辐照前,初始的宇生核素浓度为零(无继承性核素),在暴露期间(t)内假设不受侵蚀速率 ε 的影响[暴露年代计算公式如(7)所示],或者所受侵蚀速率 ε 为恒定值且可以估算出来,则也可以根据公式(6)推导出暴露年代计算公式:

$$t = -\frac{1}{\lambda + \mu\varepsilon}\ln\left[1 - \frac{N \bullet (\lambda + \mu\varepsilon)}{p}\right] \quad (8)$$

1.4 双核素的应用

Lal 和 Arnold(1985)最先提出了双核素计算方法,对于核素对的应用,经常使用的核素对组合是^{10}Be 和^{26}Al,其主要原因是:两者同时来自于石英矿物中,具有相同的地球化学特征;两者的半衰期可以用来估算第四纪以来的暴露年代,且半衰期差异较大,便于对比;两者的生成速率计算相对成熟;$n(^{26}Al)/n(^{10}Be)$值[即同一样品中宇生核素 Al^{26} 与 Be^{10}浓度(单位为 atom/g)的比值]稳定,基本不受纬度、海拔高度、深度以及时间等因素的影响(Nishiizumi et al., 1989; Gosse and Phillips, 2001)。具体情况如下:

在假设样品初始宇生核素浓度为零的情况下,其地貌体表面宇生核素^{10}Be 和^{26}Al 的浓度与时间和侵蚀速率的函数关系根据公式(6)可得:

$$N_{Be}(t) = \frac{p_{Be}(0)}{\lambda_{Be} + \mu\varepsilon}[1 - e^{-(\lambda_{Be}+\mu\varepsilon)t}] \quad (9)$$

$$N_{Al}(t) = \frac{p_{Al}(0)}{\lambda_{Al} + \mu\varepsilon}[1 - e^{-(\lambda_{Al}+\mu\varepsilon)t}] \quad (10)$$

式(10)与式(9)两边分别相除得:

$$\frac{N_{Al}(t)}{N_{Be}(t)} = \frac{\dfrac{p_{Al}(0)}{\lambda_{Al} + \mu\varepsilon}[1 - e^{-(\lambda_{Al}+\mu\varepsilon)t}]}{\dfrac{p_{Be}(0)}{\lambda_{Be} + \mu\varepsilon}[1 - e^{-(\lambda_{Be}+\mu\varepsilon)t}]} \quad (11)$$

对于公式(11),当侵蚀速率 $\varepsilon=0$ 时:

$$\frac{N_{Al}(t)}{N_{Be}(t)} = \frac{p_{Al}(0)\lambda_{Be}[1 - e^{-\lambda_{Al}t}]}{p_{Be}(0)\lambda_{Al}[1 - e^{-\lambda_{Be}t}]} \quad (12)$$

随着暴露时间的增加,$N_{Al}(t)/N_{Be}(t)$值将逐渐减少,当 t 趋于$+\infty$时,公式(12)将变为:

$$\frac{N_{Al}(t)}{N_{Be}(t)} = \frac{p_{Al}(0)\lambda_{Be}}{p_{Be}(0)\lambda_{Al}} \quad (13)$$

在高纬海平面,宇生核素^{26}Al 和^{10}Be 的生成速率比值采用 Balco(2009)结果约为 6.75,因此最终的 $N_{Al}(t)/N_{Be}(t)= 3.43$(之前学者由于生成速率比值的差异,计算结果为 2.88)。

对于公式(11),当处于"稳定侵蚀状态$\left[即\ t >> \dfrac{1}{\lambda+\mu\varepsilon)}\right]$"时:

$$\frac{N_{Al}(t)}{N_{Be}(t)} = \frac{p_{Al}(0)(\lambda_{Be} + \mu\varepsilon)}{p_{Be}(0)(\lambda_{Al} + \mu\varepsilon)} \quad (14)$$

利用 $n(^{26}Al)/n(^{10}Be)$对^{10}Be 浓度作图,根据公式(12)和(14)可以绘制两条曲线,如图 1 所示[由张志刚(2014)中原始数据经过 http://hess.ess.washington.edu/math/al_be_v23/al_be_multiple_v23.html 模型计算版],上部的曲线由公式(12)确定,代表样品突然暴露于地表,没有遭受侵蚀,而下面的虚线由公式(14)确定,曲线代表的是样品达到了侵蚀平衡状态,中间的区域则被称之为"稳定侵蚀岛"。该曲线图可以根据实验结果(^{10}Be 和^{26}Al 的浓度)对样品进行如下分析(Lal, 1991; 李英奎 等, 2005):

如果样品年代数据落在"稳定侵蚀岛"(Island of steady state erosion)的上方和右侧的"禁止区"(forbidden zone)内,该数据本身将不具备任何地学意义,一般可能由于样品处理和测量过程中的问题或不确定性造成,也可能由于样品具有相对较高的^{26}Al 背景值,从而造成 $n(^{26}Al)/n(^{10}Be)$值偏高的情况;如果样品数据落在上面的实心曲线上(或一定误差范围内),说明样品本身未经历明显的埋藏或侵蚀过程;如果样品数据落在下面的曲线上(或一定误差范围内),则意味着样品已经处于侵蚀平衡状态;如果样品年代数据落在"稳定侵蚀岛"内,说明样品尚未达到侵蚀平衡状态,既存在着表面侵蚀,又经历了一定的暴露时间;如果样品数据落在"稳定侵蚀岛"下方说明样品曾经历过一次或多次遮挡或埋藏事件。

因此,我们可知宇生核素暴露测年技术在年代计算过程中会进行相关假设,其中继承性核素由于难以测定,通常会假设为零。在冰川地貌暴露测年研究过程中,随着测年数据的不断积累尤其是小冰期和新冰期冰碛物的暴露测年研究,越来越多的学者注意到继承性核素的影响。

2 继承性核素在冰川地貌暴露测年中的研究现状

自从 Davis 等(1999) 首次利用 TCN ^{10}Be 和^{26}Al 测年技术测定加拿大北极东部冰碛垄上漂砾的暴露年代,发现继承性核素的影响可以忽略后,随着冰川地貌暴露测年研究不断积累,许多学者开始关注继承性核素的影响。关于冰川地貌宇生核素继承性的研究进展已在"继承性核素在冰川地貌中的研究进展"一文中详细介绍,文中分析了 2009~2017 年期间 54 篇全球关于第四纪冰川宇生核素继承性研究文献,搜集了文献中 TCN 暴露测年的采样环境(纬度、经度、样品类型),数据分布如图 2 所示,其对应的研究区(1~24)如表 1 所示。

在目前关于继承性宇生核素对 TCN 暴露测年

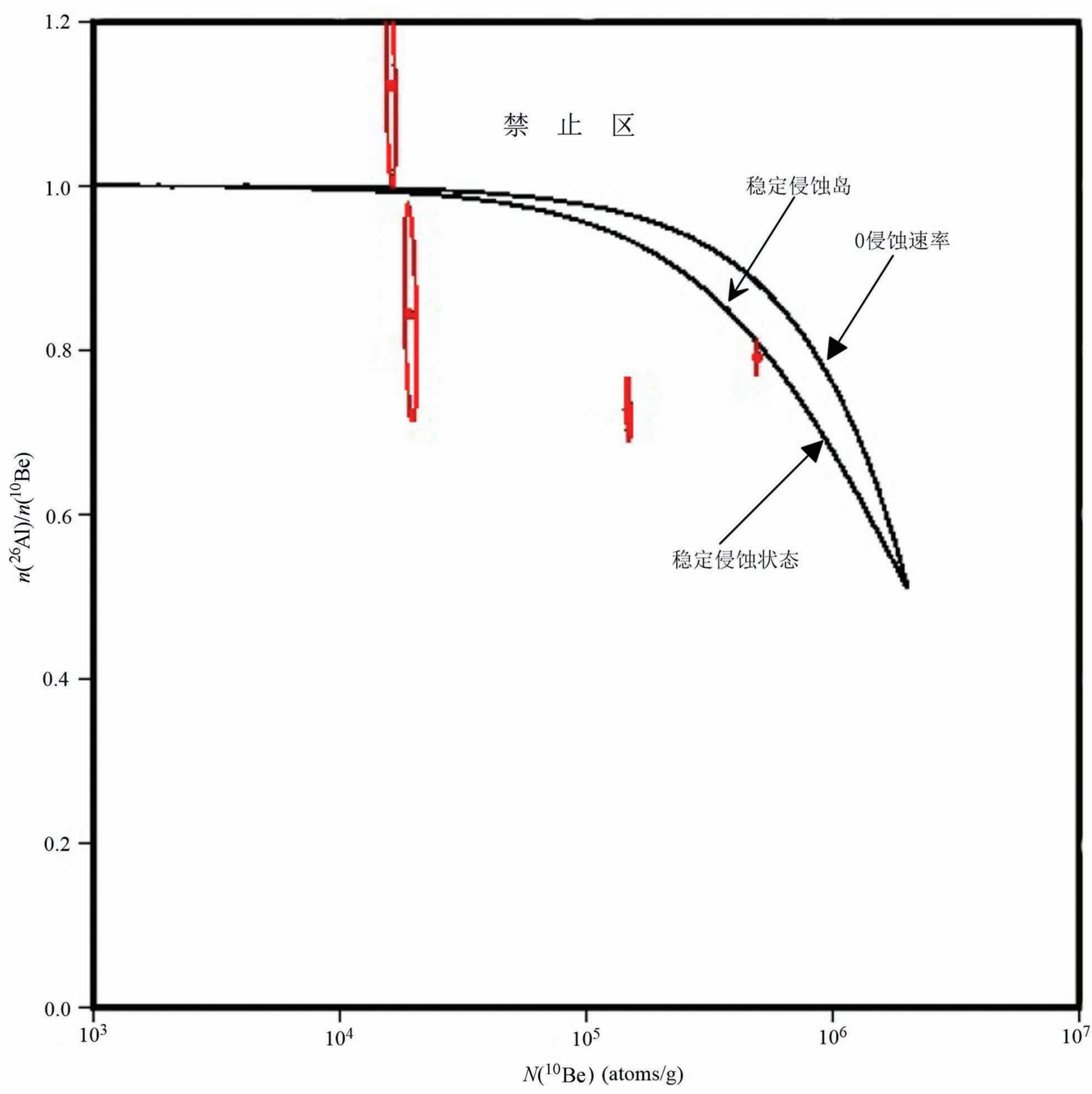

图 1 稻城古冰帽区地表岩石 $n(^{26}Al)/n(^{10}Be)$ 值随 ^{10}Be 浓度变化

Fig. 1 $n(^{26}Al)/n(^{10}Be)$ ratio as a function of ^{10}Be concentration

的影响(有无影响? 是否可以忽略?)的研究中存在着不同认识。其中有些学者认为继承性核素的影响很小,可以忽略:一是通过模型统计分析,Putkonen and Swanson(2003)统计分析了 638 个漂砾的暴露年代,认为仅有低于 3%的漂砾存在先前暴露(即继承性核素);Heyman 等(2011a)利用“先期暴露”和“不完全暴露”模型分析青藏高原(1420 个冰川漂砾)、北半球大陆冰盖(631 个冰川漂砾)、现代冰川(208 个冰川漂砾)的暴露年代数据,认为先期暴露(继承性核素)对暴露测年的影响远小于后期地质地貌过程(不完全暴露)的影响。二是对现代冰川冰碛物进行暴露测年研究,认为核素残留的影响微不足道。Hein 等(2017)对南美洲南部巴塔哥尼亚中部(Patagonia)冰川前缘的小砾石(pebble)进行 TCN ^{10}Be 浓度测试,发现冰川冰碛物的继承性宇生核素浓度非常小,可以忽略不计。Ciner 等(2017)研究表明,冰碛垄表面的漂砾和小砾石(cobbles)继承性核素浓度非常小,可以忽略不计。另外,有学者

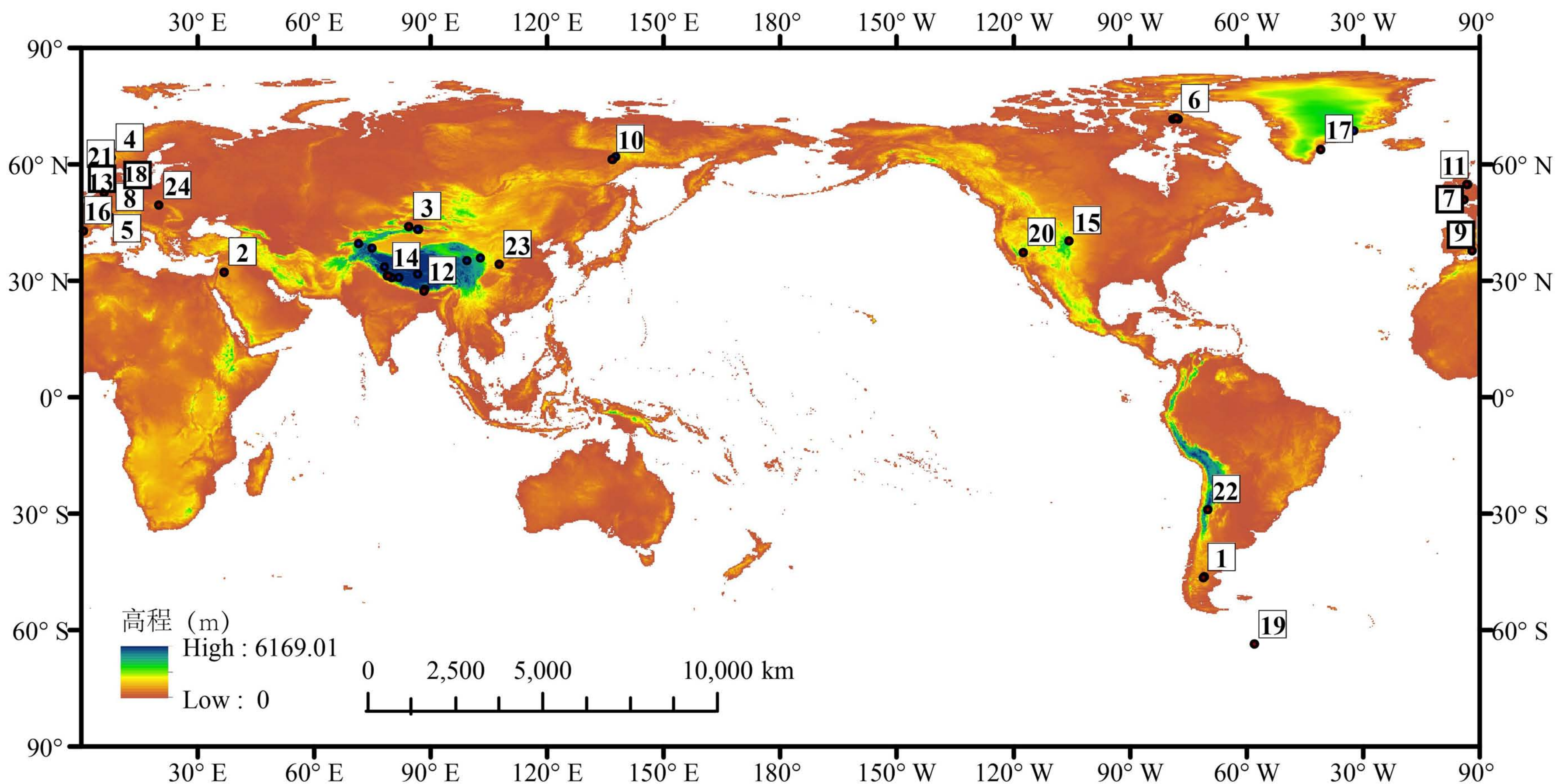

图2 全球TCN暴露测年继承性核素研究位置分布图（源于张梦媛等[1]）

Fig. 2 The location of published TCN inheritance studies of the global （from Zhang Mengyuan et al.[1]）

表 1 全球 TCN 暴露测年继承性核素研究信息(源于张梦媛等[1])

Table 1 Information of TCN inheritance studies of the whole world (from Zhang Mengyuan et al.[1])

编号	研究区	数据来源
1	巴塔哥尼亚(Patagonia)	Hein et al., 2009, 2017
2	土耳其(Turkey)	Zahno et al., 2010; Ciner et al., 2015, 2017
3	天山(Tianshan Mts.)	Abramowski et al., 2006; Murari et al., 2014; Li Yingkuiet al., 2011, 2014; Li Ya'nan et al., 2016; Blomdin et al., 2016
4	挪威(Norway)	Matthews et al., 2017
5	欧洲阿尔卑斯山(European Alps)	Ivy-Ochs et al., 2007; Akcar et al., 2014; Wirsig et al., 2016
6	巴芬岛(Baffin Island)	Briner et al., 2005, 2014
7	达特穆尔(Dartmoor)	Gunnell et al., 2013
8	瑞士山谷冰川(Arolla)	Abbühl et al., 2009
9	东西伯利亚(SE Iberia)	Angel et al., 2014
10	科迪勒拉冰盖(CIS)	Stroeven et al., 2010, 2014
11	英格兰西北部的湖区(northwest England)	Wilson et al., 2013
12	锡金(Sikkim)	Abrahami et al., 2016
16	比利牛斯山(Pyrenees)	Crest et al., 2017
13	爱尔兰冰盖(BIIS)	Ballantyne, 2012
14	青藏高原地区[Xizang(Tibet]	Barnard et al., 2004; Owen et al., 2006; Seong et al., 2009; Heyman et al., 2011b; Wang Jie et al., 2013; Zech et al., 2013; Xu Xiangke and Yi Chaolu, 2014; Rades et al., 2015; Grin et al., 2016
15	科罗拉多州(Colorado)	Benson et al., 2007; Dühnforth and Anderson, 2011
17	格陵兰(Greenland)	Dyke et al., 2014; Strunk et al., 2017
18	丹麦(Denmark)	Houmark-Nielsen et al., 2012
19	古斯塔夫冰流(Gustav Ice Stream)	Nyvlt et al., 2014
20	死亡谷(Death Valley)	Owen et al., 2011
21	苏格兰(Cairngorm Mountains)	Phillips et al., 2006
22	智利北部(Encierro)	Zech et al., 2006
23	太白山脉(Tai Bai Mountains)	Zhang Wei et al., 2016
24	高塔特拉山脉(Polish High Tatra Mountains)	Makos et al., 2013

认为继承性核素影响比较大,主要是通过同一地貌体不同样品的年代分布来判断,Glasser 等(2012)对不列颠群岛阿轮(Aran)山脉基岩上 8 个样品进行 TCN ^{10}Be 和^{26}Al 暴露测年研究,发现其中有两个样品的暴露年龄要比其他样品的年龄大得多,可能受到核素继承性的影响。Dortch 等(2013)对青藏高原地区西部喜马拉雅山,帕米尔山脉和天山山脉进行 TCN 暴露测年研究,在分析的 595 个样品中,8%的样品受到核素继承性的影响。Dyke 等(2014)对格陵兰冰原(Gris)进行 TCN ^{10}Be 暴露测年研究,认为暴露年龄更大的样品可能受到核素继承性的影响。Davis 等(2015)利用 TCN ^{10}Be 和^{26}Al 暴露测年技术对 Katahdin 山脉冰川地貌进行研究,发现 Katahdin 盆地内冰碛物暴露年代比 Littleton 区域冰碛物暴露年龄大,其中一个原因可能受到宇生核素继承性的影响。Blomdin 等(2016)重新计算了天山先前发表的^{10}Be 暴露年代并结合新的测年数据(共计 114 个),发现大约 60%的测年结果受继承性核素的影响。Li Ya'nan 等(2016)利用 TCN^{10}Be 测年技术对天山山脉小冰期冰川地貌进展进行暴露测年研究,发现来自小型冰川(小而薄)的冰碛物较易受到继承性核素的影响。

综上所述,关于冰川地貌继承性核素对暴露测年研究的影响是一个非常复杂的问题,随着 TCN 暴露测年技术的发展、测年精度要求不断提高,继承性核素愈加受到众多学者的关注和研究,这将有利于 TCN 暴露测年技术误差的定量化研究,从而更加准确地测定冰川地貌的真实年代。

3　继承性核素对冰川地貌暴露测年结果影响的定量分析方法

3.1　样品是否受继承性核素影响的判断

由于漂砾是较为常见的测年物质,大多数学者通常将其产生继承性核素的途径归纳为以下三种(Dortch et al., 2013; Wilson et al., 2013; Murari et al., 2014):其一为原地暴露或者来自于先前曾经暴露过的基岩上。其二为岩壁上掉落在冰川表面上的砾石,而该砾石曾经暴露,携带了先前暴露过程中的

宇生核素。第三,由于先前冰川作用而暴露的砾石,在后期的冰川作用中再次堆积于冰碛垄表面而造成的继承性核素残留。

通常情况下,通过同一地貌样品组年代数据的分布情况来判断样品是否受到继承性核素的影响,如果测年数据中有明显偏老的数据,则该数据通常被认为是受到继承性核素的影响。Stroeven 等(2014)在测定 Cordilleran 冰盖冰进事件时,样品 YK08-10 的年代(154.3 ka)明显高于邻近地貌其它砾石的年代(33.5~84.4 ka),被认为是严重受到继承性核素的影响。Li Ya'nan 等(2016)利用宇生核素^{10}Be 暴露测年技术测定天山东部小冰期时形成的冰川地貌时, UG3、HDBC 和 UGS 冰碛垄漂砾组的年代数据分散而且明显老于小冰期,其中 HDBC 冰碛垄表面漂砾的年代分布从 1.3 ka 到 9.3 ka,被认为是受到继承性核素的影响。Zech 等(2006)应用 TCN ^{10}Be 暴露测年技术对智利北部的 Encierro 山谷冰川地貌进行暴露测年研究,研究结果表明该冰川地貌年代数据中存在异常偏老的暴露年龄,原因可能是受到了核素继承性的影响。Grin 等(2016)在帕米尔高原冰川地貌年代学测定过程中,对 Muksu 区域冰川退却年代测定中,通过剔除较为年轻的数据(由于冰碛垄的剥蚀、降低、变缓而出露的新的砾石)和较老的数据(由于继承性核素的影响),最后取年代数据的平均值作为冰退的年代。此外,随着^{26}Al 测试精度的提高,利用^{26}Al/^{10}Be 浓度比来检验样品是否具有复杂的埋藏—暴露历史(如果比值落在“稳定侵蚀岛”下方,则说明样品具有复杂的埋藏暴露历史),其具体原理在 1.4 中双核素的应用中详细介绍。然而,该方法由于需要测试^{26}Al 浓度,测试成本相应增加,但是为了提高测年数据的准确程度,将来可以尝试测量同一样品的^{10}Be 和^{26}Al 浓度,除了可以对比测年结果是否准确,还可以反映样品的暴露历史,有助于进行地貌过程解释。

3.2 继承性核素对暴露测年结果影响的定量分析方法

继承性核素在计算过程中通常假设为 0,究其原因是由于难以获知,而且至今没有简单或完全可靠的方法来检测它存在或评估其大小(Benson et al., 2007;Dortch et al., 2013)。Matthews 等(2017)认为利用现代冰川区域已知退却历史的冰碛物进行宇生核素暴露测年研究是检验核素继承性的最好方法之一。Davis 等(1999)首次利用现代冰川沉积物测试核素继承性。王建等(2010)测定了海螺沟现代冰碛物(该区冰川属于海洋性冰川,冰川运动速度快,对冰碛物的侵蚀作用强,理论上继承性核素浓度低于大陆性冰川作用区)中 TCN ^{10}Be 的浓度,认为该区域现代冰碛物中继承性核素对暴露年代的影响一般不大于 0.61 ka; Murari 等(2014)测定了 Chorabari 冰川表面漂砾的^{10}Be 暴露年代,研究表明可能有多达 0.5 ka ^{10}Be 核素残留。因此,可以通过研究区现代冰碛物中继承性核素产生的暴露年代来定量估算继承性核素对古冰川地貌样品暴露测年的影响程度。一些学者在冰川地貌暴露测年过程中会选择少数现代冰川冰碛物样品进行继承性核素残留测试(Barnard et al., 2004; Heyman et al., 2011b;Li Ya'nan et al., 2016),来分析继承性核素对暴露测年结果的影响。

3.3 样品采集中如何降低继承性核素的影响

李英奎等(2005)认为对冰川地貌暴露年代的测定需要采用多样品测试方法,对较老和较大规模的冰碛物需要采集 6—7 个样品,而对较小规模冰碛物,也需要采集 1~4 个样品。王建等(2010)认为在利用宇生核素进行冰碛物暴露年代测定时,需考虑核素残留的影响,采集漂砾样品时,要尽量选取具有明显冰川磨蚀痕迹的砾石。Matthews 等(2017)研究认为在冰川地貌暴露年代测定方面,应采取多样化的抽样方法,即选用大量的小砾石组成为一个样本,而不是使用单个的大漂砾,这将会有利于减少核素继承性误差。

此外,如果研究区无现代冰川分布,或者采集现代冰川样品比较困难,也可以尝试采集冰碛垄底部(2~3 m 以下)样品,通过顶部样品和底部样品核素浓度的差值来消除继承性核素的影响。其假设原理是:冰碛垄形成时顶部样品和底部样品是同时沉积的,如果受到继承性核素的影响,那么这两种样品内部的继承性核素是一样的,后期暴露过程中,顶部样品既生成新的核素,同时由于放射性元素衰减一部分核素,而底部的样品通常被认为只有衰减。因此,可以通过顶部样品和底部样品核素浓度的差值来消除继承性核素的影响。Wang Jian 等(2006)在测量沙鲁里山稻城古冰帽库照日最老冰碛垄时曾采用这种方法。

4 结论

综上所述,随着 AMS 测试技术和宇生核素暴露测年技术的不断发展,随着对冰川地貌年代分辨率和准确度要求的提高,利用核素对

$n(^{26}Al)/n(^{10}Be)$值[即同一样品中宇生核素 Al^{26} 与 Be^{10} 浓度(单位为 atom/g)的比值]可以了解样品曾经的“暴露历史”并结合同一地貌样品组暴露年代分布可以初步判断样品是否受到继承性核素的影响；通过研究区现代冰碛物宇生核素暴露测年可以定量估算继承性核素的影响程度；可以尝试通过古冰川地貌(冰碛垄)顶部样品和底部样品核素浓度差并结合其它科学采样方法可以降低继承性核素的影响。

此外，冰川属性(冷底冰川、暖底冰川)、体积、研究区岩性、气候特征等的差异也会对继承性核素研究造成影响，有待于进一步从理论和实验进行研究。

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注 释 / Note

❶ 张梦媛，梅静，张志刚，王建，梁兴江. 承性宇生核素在冰川地貌暴露测年中的研究进展. 地球环境学报(待刊).

❶ Zhang Mengyuan, Mei Jing, Zhangzhigang, Wang Jian, Liang Xingjiang. Research progress of inherited cosmogenic nuclide in Exposure dating of glacial geomorphology. Journal of Earth Environment(In press).

参 考 文 献 / References

(The literature whose publishing year followed by a “&” is in Chinese with English abstract; The literature whose publishing year followed by a “#” is in Chinese without English abstract)

李英奎，Harbor J，刘耕年，周力平，崔之久. 2005. 宇宙核素地学研究的理论基础与应用模型. 水土保持研究，12(4)：139～145.

吕延武，梁欧博，黄飞鹏. 2019. 就地生成宇宙成因核素年龄计算模式应用. 地质论评，65(4)：1021～1030.

张志刚. 2014 稻城古冰帽第四纪冰川年代学研究. 南京：南京师范大学博士学位论文.

张志刚，王建，徐孝彬，赵志军，白世彪. 2013. 暴露时间对利用原地生宇生核素估算至大侵蚀速率的影响. 地质论评，59(5)：924～932.

张志刚，王建，张梦媛，梅静. 2017. 冰冰碛垄表面碎屑物质宇生核素暴露测年可行性研究. 地质论评，63(6)：1576～1584.

张志刚，徐孝彬，王建，白世彪，常直杨. 2014. 青藏高原地区宇生核素暴露年代数据存在的问题探讨. 地质论评，60(6)：1359～1369.

周尚哲，李吉均. 2003. 第四纪冰川测年研究新进展. 冰川冻土，25(6)：660～666.

Abbuhl L M, Akcar N, Strasky S, Graf A A, Ivy-Ochs S, Schluchter C. 2009. A zero-exposure time test on an erratic boulder: evaluating the problem of pre-exposure in surface exposure dating. Eiszeitalter und Gegenwart Quaternary Science Journal, 58(1): 1～11.

Abrahami R, Beek P V D, Huyghe P, Hardwick E, Carcaillet J. 2016. Decoupling of long-term exhumation and short-term erosion rates in the Sikkim Himalaya. Earth Planetary Science Letters, 433: 76～88.

Abramowski U, Bergau A, Seebach D, Zech R, Glaser B, Sosin P, Kubik P W, Zech W. 2006. Pleistocene glaciations of Central Asia: results from ^{10}Be surface exposure ages of erratic boulders from the Pamir (Tajikistan) and the Alay—Turkestan range (Kyrgyzstan). Quaternary Science Reviews, 25: 1080～1096.

Akcar N, Ivy-Ochs S, Deline P, Alfimov V, Kubik P W, Christl M Schluchter C. 2014. Minor inheritance inhibits the calibration of the ^{10}Be production rate from the AD 1717 Val Ferret rock avalanche, European Alps. Journal of Quaternary Science, 29(4): 318～328.

Angel Rodés, Raimon Pallàs, Maria Ortuño, Eduardo Garcia-Melendez, Eulàlia Masana. 2014. Combining surface exposure dating and burial dating from paired cosmogenic depth profiles. Example of El Limite alluvial fan in Huércal—Overa basin (SE Iberia). Quaternary Geochronology, 19(19): 127～134.

Applegate P J, Urban N M, Laabs B J C, Keller K, Alley R B. 2010. Modeling the statistical distributions of cosmogenic exposure dates from moraines. Geoscientific Model Development, 3(1):297～307.

Applegate P J, Urban N M, Keller K, Lowell T V, Laabs B J C, Keller K, Alley R B. 2012. Improved moraine age interpretations through explicit matching of geomorphic process models to cosmogenic nuclide measurements from single landforms. Quaternary Research, 77(2):293～304.

Balco G. 2011. Contributions and unrealized potential contributions of cosmogenic-nuclide exposure dating to glacier chronology, 1990～2010. Quaternary Science Reviews, 30(1～2): 3～27.

Balco G, Briner J, Finkel R C, Rayburn J A, Ridge J C, Schaefer J M. 2009. Regional beryllium-10 production rate calibration for late-glacial northeastern North America. Quaternary Geochronology, 4: 93～107.

Ballantyne C K. 2010. Extent and deglaciation chronology of the last British—Irish Ice Sheet: implications of exposure dating using cosmogenic isotopes. Quaternary International, 279～80(4): 35～36.

Barnard P L, Owen L A, Finkel R C. 2004. Style and timing of glacial and paraglacial sedimentation in a monsoon-influenced high Himalayan environment, the upper Bhagirathi Valley, Garhwal Himalaya. Sedimentary Geology, 165(3): 199～221.

Benson L, Madole R, Kubik P, McDonald R. 2007. Surface-exposure ages of Front Range moraines that may have formed during the Younger Dryas, 8.2 cal ka, and Little Ice Age events. Quaternary Science Reviews, 26(11): 1638～1649.

Blomdin R, Stroeven A P, Harbor J M, Lifton N A, Heyman J, Gribenski N, Petrakov D A, Caffee M W, Ivanov M N, Hattestrand C, Rogozhina I, Usubaliev R. 2016. Evaluating the timing of former glacier expansions in the Tian Shan: A key step towards robust spatial correlations. Quaternary Science Reviews, 153: 78～96.

Briner J P, Lifton N A, Miller G H, Refsnider K, Anderson R, Finkel R C. 2014. Using in situ, cosmogenic ^{10}Be, ^{14}C, and ^{26}Al to decipher the history of polythermal ice sheets on Baffin Island, Arctic Canada. Quaternary Geochronology, 19: 4～13.

Briner J P, Miller G H, Davis P T, Finkel R C. 2005. Cosmogenic exposure dating in arctic glacial landscapes: implications. Canadian Journal of Earth Sciences, 42(1): 67～84.

Brook E J, Kurz M D, Ackert R P, DentonErik G H, Brown Grant T, Raisbeck M, Francoise Yiou. 1993. Chronology of Taylor Glacier advances in Arena Valley, Antarctica, Using in situ cosmogenic ^{3}He and ^{10}Be. Quaternary Research, 39(1): 11～23.

Brook E J, Nesje A, Lehman S J, Raisbeck D M, Françoise Yiou. 1996. Cosmogenic nuclide exposure ages along a vertical transect in western Norway: Implications for the height of the Fennoscandian ice sheet. Geology, 24(3): 207~210.

Brown E T, Edmond J M, Raisbeck G M, Yiou F, Kurz M D, Brook E J. 1991. Examination of surface exposure ages of Antarctic moraines using in situ produced ^{10}Be and ^{26}Al. Geochimica et Cosmochimica Acta, 55(8): 2269~2283.

Ciner A, Sarikaya M A, Yildirim C. 2015. Late Pleistocene piedmont glaciations in the Eastern Mediterranean; insights from cosmogenic ^{36}Cl dating of hummocky moraines in southern Turkey. Quaternary Science Reviews, 116:44~56.

Ciner A, Sarikaya M A, Yildirim C. 2017. Misleading old age on a young landform? The dilemma of cosmogenic inheritance in surface exposure dating: Moraines vs. rock glaciers. Quaternary Geochronology, 42:76~88.

Crest Y, Delmas M, Braucher R, Gunnell Y, Calvet M, ASTER Team. 2017. Cirques have growth spurts during deglacial and interglacial periods: Evidence from ^{10}Be and ^{26}Al nuclide inventories in the central and eastern Pyrenees. Geomorphology, 278: 60~77.

Davis P T, Bierman P R, Corbett L B, Finkel R C. 2015. Cosmogenic exposure age evidence for rapid Laurentide deglaciation of the Katahdin area, west—central Maine, USA, 16 to 15ka. Quaternary Science Reviews, 116: 95~105.

Davis P T, Bierman P R, Marsella K A, Caffee M W, Southon J R. 1999. Cosmogenic analysis of glacial terrains in the eastern Canadian Arctic: a test for inherited nuclides and the effectiveness of glacial erosion. Annals of Glaciology 28(28): 181~188.

Dortch J M, Owen L A, Caffee M W. 2013. Timing and climatic drivers for glaciation across semiarid western HimalayaneTibetan orogen. Quaternary Science Reviews, 78(11): 188~208.

Dühnforth M, Anderson R S. 2011. Reconstructing the glacial history of Green Lakes Valley, North Boulder Creek, Colorado Front Range. Arctic Antarctic & Alpine Research, 43(4): 527~542.

Dyke A S, Andrews J T, Clark J H. 2002. The Lauentide and Innuitian ice sheets during the Last Glacial Maximum. Quaternary Science Reviews, (21): 9~31.

Dyke L M, HughesA L C, Murray T, Hiemstra J F, Andresen C S, Rodes A. 2014. Evidence for the asynchronous retreat of large outlet glaciers in southeast Greenland at the end of the last glaciation. Quaternary Science Reviews, 99(9): 244~259.

Glasser N F, Hughes P D, Fenton C, Schnabel C, Rother H. 2012. ^{10}Be and ^{26}Al exposure-age dating of bedrock surfaces on the Aran ridge, Wales: evidence for a thick Welsh Ice Cap at the Last Glacial Maximum. Journal of Quaternary Science, 27(1): 97~104.

Gosse J C, Phillips F M. 2001. Terrestrial in situcosmogenic nuclides: theory and application. Quaternary Science Reviews, 20(14): 1475~1560.

Grin E, Ehlers T A, Schaller M, Sulaymonova V, Ratschbacher L, Gloaguen R. 2016. ^{10}Be Surface-Exposure Age Dating of the Last Glacial Maximum in the Northern Pamir (Tajikistan). Quaternary Geochronology, 34: 47~57.

Gunnell Y, Jarman D, Braucher R, Calvet M, Delmas M, Leanni L, Bourles D, Arnold M, Aumaitre G, Keddaouche K. 2013. The granite tors of Dartmoor, Southwest England: rapid and recent emergence revealed by Late Pleistocene cosmogenic apparent exposure ages. Quaternary Science Reviews, 61(2): 62~76.

Hallet B, Putkonen J. 1994. Surface dating of dynamic landforms: young boulders on aging moraines. Science, 265(5174): 937~940.

Hein A S, Cogez A, Darvill C M, Mendelova M, Kaplan M R, Herman F, Dunai T J, Norton K, Xu Sheng, Christl M, Rodes A. 2017. Regional mid-Pleistocene glaciation in central Patagonia. Quaternary Science Reviews, 164: 77~94.

Hein A S, Hulton N R J, Dunai T J, Schnabel C, Kaplan M R, Naylor M, Xu Sheng. 2009. Middle Pleistocene glaciation in Patagonia dated by cosmogenic-nuclide measurements on outwash gravels. Earth & Planetary Science Letters, 286(1): 184~197.

Heyman J, Stroeven A P, Caffee M W, Hattestrand C, Harbor J M, Li Yingkui, Alexanderson H, Zhou Liping, Hubbard A. 2011b. Palaeoglaciology of Bayan Har Shan, NE Tibetan Plateau: exposure ages reveal a missing LGM expansion. Quaternary Science Reviews, 30(15): 1988~2001.

Heyman J, Stroeven A, Harbor J, Caffee M W. 2011a. Too young or too old: evaluating cosmogenic exposure dating based on an analysis of compiled boulder exposure ages. Earth and Planetary Science Letters, 302(1/2): 71~80.

Houmark-Nielsen M, Linge H, Fabel D, Schnabel C, Xu Sheng, Wilcken K M, Binnie S. 2012. Cosmogenic surface exposure dating the last deglaciation in Denmark: Discrepancies with independent age constraints suggest delayed periglacial landform stabilisation. Quaternary Geochronology, 13(6): 1~17.

Ivy-Ochs S, Kerschner H, Schlüchter C. 2007. Cosmogenic nuclides and the dating of Lateglacial and Early Holocene glacier variations: The Alpine perspective. Quaternary International, 164(2): 53~63.

Ivy-Ochs S, Schaller M. 2009. Chapter 6 Examining Processes and Rates of Landscape Change withCosmogenic Radionuclides. In: Radioactivity in the Environment. Elsevier Science Technology: 231~294.

Lal D, Arnold J R. 1985. Tracing quartz through the environment. Journal of Earth System Science. 94(1): 1~5.

Lal D. 1991. Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. Earth and Planetary Science Letters, 104(2~4): 424~439.

Li Yingkui, Liu Gengnian, Chen Yixin, Li Ya'nan, Harbor J, Stroeven A, Caffee M, Zhang Mei, LiChuanchuan, Cui Zhijiu. 2014. Timing and extent of Quaternary glaciations in the Tianger Range, eastern Tian Shan, China, investigated using ^{10}Be surface exposure dating. Quaternary Science Reviews, 98: 7~23.

Li Ya'' nan, Li Yingkui, Harbor J, Liu Gengnian, Yi Chaolu, Caffee M W. 2016. Cosmogenic ^{10}Be constraints on Little Ice Age glacial advances in the eastern Tian Shan, China. Quaternary Science Reviews, 138: 105~118.

Li Yingkui, Harbor J, Liu Gengnian, Zhou Liping, Cui Zhijiu. 2005&. Theoretical background and interpretation models in-situ cosmogenic nuclides in earth sciences. Research Soil and Water Conservation, 12(4): 139~145.

Li Yingkui, Liu Gengnian, Kong Ping, Harbor J, Chen Yixin, Caffee M. 2011. Cosmogenic nuclide constraints on glacial chronology in the source area of the Urumqi River, Tian Shan, China. Journal of Quaternary Science, 26(3): 297~304.

Lü Yanwu, Liang Oubo, Huang feipeng. 2019&. Application of calculating model to in-situ cosmogenic nuclides age. Geological Review, 65(4): 1021~1030.

Makos M, Nitychoruk J, Zreda M. 2013. The Younger Dryas climatic conditions in the Za Mnichem Valley (Polish High Tatra Mountains) based on exposure-age dating and glacier—climate modelling. Boreas, 42(3): 745~761.

Matthews J A, Shakesby R A, Fabel D. 2017. Very low inheritance in cosmogenic surface exposure ages of glacial deposits: A field experiment from two Norwegian glacier forelands. Holocene, 27(9): 1~9.

Murari M K, Owen L A, Dortch J M, Caffee M W, Dietsch C, Fuchs M, Haneberg W C, Sharma M C, Townsend-Small A. 2014. Timing and climatic drivers for glaciation across monsoon-influenced regions of the Himalayan - Tibetan orogen. Quaternary Science Reviews, 88(6): 159~182.

Nishiizumi K, Winterer E L, Kohl C P, Klein J, Middleton R, Lal D, Arnold J R. 1989. Cosmic ray production rates of ^{10}Be and ^{26}Al in quartz from glacially polished rocks. Journal of Geophysical Research, 94: 17907~17915.

Nyvlt D, Braucher R, Engel Z, Mlcoch B, ASTER Team. 2014. Timing of the Northern Prince Gustav Ice Stream retreat and the deglaciation of northern James Ross Island, Antarctic Peninsula during the last glacial - interglacial transition. Quaternary Research, 82(2): 441~449.

Owen L A, Caffee M W, Bovard K R, Finkel R C, Sharma M C. 2006. Terrestrial cosmogenic nuclide surface exposure dating of the oldest glacial successions in the Himalayan orogen: Ladakh Range, northern India. Geological Society of America Bulletin, 118(3):383~392.

Owen L A, ChenJie, Hedrick K A, Caffee M W, Robinson A C, Schoenbohm L M, Yuan Zhaode, Li Wenqiao, Imrecke D B, Liu Jinfeng. 2012. Quaternary glaciation of the Tashkurgan Valley, Southeast Pamir. Quaternary Science Reviews, 47(4): 56~72.

Owen L A, Dortch J M. 2014. Nature and timing of Quaternary glaciation in the Himalayan—Tibetan orogen. Quaternary Science Reviews, 88(88):14~54.

Owen L A, Frankel K L, Knott J R, Reynhout S, Finkel R C, Dolan J F, Lee J. 2011. Beryllium-10 terrestrial cosmogenic nuclide surface exposure dating of Quaternary landforms in Death Valley. Geomorphology, 125(4): 541~557.

Phillips W M, Hall A M, Mottram R, Fifield K L, Sugden D E. 2006. Cosmogenic ^{10}Be and ^{26}Al exposure ages of tors and erratics, Cairngorm Mountains, Scotland: Timescales for the development of a classic landscape of selective linear glacial erosion. Geomorphology, 73(3): 222~245.

Putkonen J, Swanson T. 2003. Accuracy of cosmogenic ages for moraines. Quaternary Research, 59: 255~261.

Rades E F, Hetzel R, Strobl M, Xu Qiang, Ding Lin. 2015. Defining rates of landscape evolution in a south Tibetan graben with in situ-produced cosmogenic ^{10}Be. Earth Surface Processes & Landforms, 40(14): 1862~1876.

Seong Y B, Owen L A, Yi Chaolu, Finkel R C. 2009. Geomorphology of anomalously high glaciated mountains at the northwestern end of Tibet: Muztag Ata and Kongur Shan. Geomorphology, 103(2): 227~250.

Stroeven A P, Fabel D, Codilean A T, Kleman J, Clague J J, Miguens-Rodriguez M, Xu Sheng. 2010. Investigating the glacial history of the northern sector of the Cordilleran Ice Sheet with cosmogenic ^{10}Be concentrations in quartz. Quaternary Science Reviews, 29(25): 3630~3643.

Stroeven A P, Fabel D, Margold M, Clague J J, Xu Sheng. 2014. Investigating absolute chronologies of glacial advances in the NW sector of the Cordilleran Ice Sheet with terrestrial in situ cosmogenic nuclides. Quaternary Science Reviews, 92(92): 429~443.

Strunk A, Knudsen M F, Egholm D L, Jansen J D, Levy L B, Jacobsen B H, Larsen N K. 2017. One million years of glaciation and denudation history in west Greenland. Nature Communications, 8(14199):1~8.

Wang Jian, Raisbeck G, Xu Xiaobin, Yiou F, Bai Shibiao. 2006. In situ cosmogenic ^{10}Be dating of the Quaternary glaciations in the southern Shaluli Mountain on the Southeastern Tibetan Plateau. Science in China Series D: Earth Sciences, 49(12): 1291~1298.

Wang Jie, Kassab C, Harbor J M, Caffee M W, Cui Hang, Zhang Guoliang, 2013. Cosmogenic nuclide constraints on late Quaternary glacial chronology on the Dalijia Shan, northeastern Tibetan Plateau. Quaternary Research, 79(3): 439~451.

Wilson P, Schnabel C, Wilcken K M, Vincent P J. 2013. Surface exposure dating (^{36}Cl and ^{10}Be) of post-Last Glacial Maximum valley moraines, Lake District, northwest England: some issues and implications. Journal of Quaternary Science, 28(4): 379~390.

Wirsig C, Zasadni J, Christl M, Akcar N, Ivy-Ochs S. 2016. Dating the onset of LGM ice surface lowering in the High Alps. Quaternary Science Reviews, 143: 37~50.

Xu Xiangke, Yi Chaolu. 2014. Little Ice Age on the Tibetan Plateau and its bordering mountains: Evidence from moraine chronologies. Global & Planetary Change, 116(3): 41~53.

Zahno C, Akcar N, Yavuz V, Kubik P W, Schluchter C. 2010. Chronology of Late Pleistocene glacier variations at the Uluda Mountain, NW Turkey. Quaternary Science Reviews, 29(9): 1173~1187.

Zech R, Kull C, Veit H. 2006. Late Quaternary glacial history in the Encierro Valley, northern Chile (29°S), deduced from ^{10}Be surface exposure dating. Palaeogeography Palaeoclimatology Palaeoecology, 234(2): 277~286.

Zech R, Röhringer I, Sosin P, Kabgov H, Merchel S, Akhmadaliev S, Zech W. 2013. Late Pleistocene glaciations in the Gissar Range, Tajikistan, based on ^{10}Be surface exposure dating. Palaeogeography Palaeoclimatology Palaeoecology, 369: 253~261.

Zhang Mengyuan, Mei Jing, Zhang Zhigang, Wang Jian, Xu Xiaobin. 2018. ^{10}Be Exposure Ages Obtained From Quaternary Glacial Landforms on the Tibetan Plateau and in the Surrounding Area. Acta Geologica Sinica (English Edition), 92(2):786~800

Zhang Wei, Liu Liang, Chen Yixin, Liu Beibei, Harbor J M, Cui Zhijiu, Liu Rui, Liu Xiao, Zhao Xu. 2016. Late glacial ^{10}Be ages for glacial landforms in the upper region of the Taibai glaciation in the Qinling Mountain range, China. Journal of Asian Earth Sciences, 115: 383~392.

Zhang Zhigang. 2014&. Quaternary glacial chronology of Paleo-Daocheng ice cap, Southeastern Tibetan plateau, China[D]. Nanjing: Ph. D. academic dissertation of Nanjing Normal University.

Zhang Zhigang, Wang Jian, Xu Xiaobin, Zhao Zhijun, Bai Shibiao. 2013&. Effects of exposure time on maximum erosion rate estimated using In-situ cosmogenic nuclides. Geological Review, 59(5): 924~933.

Zhang Zhigang, Xu Xiaobin, Wang Jian, Bai Shibiao, Chang Zhiyang, 2014&. Discussion of existing problems on the terrestrial cosmogenic nuclides exposure ages of Xizang (Tibetan) plateau. Geological Review, 60(1):1359~1369.

Zhang Zhigang, Wang Jian, Zhang Mengyuan, Mei Jing. 2017&. The study of cosmogenic nuclides exposure daing for the debris material on the moraine surface. Geological Review, 63(6):1576~1584.

Zhou Shangzhe, Li Jijun. 2003&. New dating results of Quaternary glaciations in China. Journal of Glaciology and Geocryology, 25(6): 660~666.

Discussion on the quantitative analysis method of the influence of inherited cosmogenic nuclide on exposure ages

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Abstract: It is usually assumed that the concentration of the nuclide (inherited nuclide) in the sample is zero before the last exposure, during the process of the In situ terrestrial cosmogenic nuclides (TCN) exposure dating. However, a large number of dating data studies have found that the results of the exposure ages of the samples will be affected by the inherited nuclides and overestimate the real age of the landform. Therefore, It is very important to reduce the influence of inherited nuclides on the exposure ages or quantitatively analyze the influence degree of inherited nuclides. It can not only provide accurate chronological data for geomorphological evolution, but also have important significance for the study of TCN exposure dating method. Therefore, this paper takes the application of the TCN exposure dating method in glacial geomorphology as an example to explore the quantitative analysis method of the effect of inherited nuclides on exposure ages based on the inherited nuclides literature and the principle of the TCN exposure dating method. The results show that: ① It is possible to preliminarily determine whether the dating results are affected by inherited nuclides by the ratio of $^{26}Al/^{10}Be$ concentration in the sample and the distribution of the ages of multiple samples at the same group; ② Quantitative analysis of the effects of inherited nuclides on exposure ages through the concentration of cosmogenic nuclides in modern glacier area; ③ the effect of inherited nuclides can be reduced by calculating the difference of the cosmogenic nuclides concentration in the top of the moraine and at a certain depth (>2~3 m). This study is of great significance for the exposure and dating of glacial geomorphology.

Keywords: inherited cosmogenic nuclides; glacial landforms; in situ terrestrial cosmogenic nuclide exposure dating; quantitative analysis

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