青藏高原冰芯有多老?

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摘要 冰芯定年是冰芯研究的第一步, 也是冰芯研究结果的根本立足点. 1992年西昆仑山地区钻取的古里雅冰芯据称超过 500 ka, 而其他青藏高原冰芯(包括距古里雅冰芯钻取点~30 km 的崇测冰芯)年代囿于全新世范围. 通过对比崇测冰芯与古里雅冰芯的稳定同位素剖面, 表明二者具有显著的一致性, 因此二者的年龄范围应该类似, 即古里雅冰芯初始定年结果可能比实际值高估了~2个量级. 若上述青藏高原冰芯年代框架得以最终证实, 则需要重新审视青藏高原冰芯的以往重建结果、以及青藏高原冰川作用异时性等诸多科学问题.

关键词 青藏高原, 冰芯, 年代, 全新世

冰芯研究是恢复过去气候环境变化记录的重要手段之一, 其主要特点是保真度好、分辨率高、信息量大等. 1987年钻取的祁连山敦德冰芯开启了青藏高原冰芯研究. 敦德冰芯初始定年结果为距冰芯底部5 m处对应40 ka, 冰芯底部(即冰-岩界面)的年代超过100 ka^[1], 但后来来自靠近冰-岩界面的一个冰芯样品的¹⁴C测年结果为 6.24 ± 0.33 ka^[2], 表明其年代可能仅囿于全新世时间尺度内. 此后钻取的达索普冰芯^[2]、普若岗日冰芯^[3]、东绒布冰芯^[4]和崇测冰芯^[5]的年代范围也仅囿于全新世(图1). 1992年在西昆仑山古里雅冰帽钻取的308.6 m冰芯是迄今在青藏高原钻取的最长冰芯. 基于放射性元素³⁶Cl的测量结果, 确定古里雅冰芯底部年代超过500 ka, 甚至最高可达~760 ka^[6], 因此古里雅冰芯被认为是非极地的最古老冰芯^[7]. Cheng等人^[8]曾根据塔里木盆地北缘的科桑石笋记录, 对古里雅冰芯的定年结果提

出质疑, 认为应将古里雅冰芯110 ka以来的稳定同位素记录压缩到60 ka左右, 才能将科桑石笋和古里雅冰芯稳定同位素记录对应起来. 由于崇测冰芯与古里雅冰芯钻取点位置相距~30 km, 而且基于崇测冰芯¹⁴C标定年龄(具体数据见表S1)已确立其年代框架^[5], 因此通过比较崇测冰芯与古里雅冰芯的稳定同位素剖面, 进一步探讨古里雅冰芯的年代范围.

西昆仑山崇测冰帽处于极大陆性冰川作用区, 是一个低积累率的典型极大陆性冰帽^[9]. 该冰帽表面运动速度甚低, 1987~1988年在平衡线附近(海拔6073 m)测得的最高运动速度仅4.16 m/a^[10], 与极地冰盖的冰面运动速度相近. 2012年10~11月在崇测冰帽钻取了2支透底冰芯(长度分别为135.8和133.8 m)和1支浅冰芯(长度分别为58.8 m). 2013年10~11月又在崇测冰帽钻取了两支透底冰芯(长度分别为216.6和208.6 m). 冰芯钻孔10 m深度处实测温

度为-12.7°C, 钻孔底部为-8.8°C, 表明该冰帽底部与基岩冻结^[11].

使用Picarro L2120-i液态水同位素分析仪对58.8和135.8 m崇测冰芯进行了稳定同位素分析, 样品 $\delta^{18}\text{O}$ 的分析精度小于0.1‰^[12]. 58.8 m崇测冰芯共采集了1956个样品, 采样分辨率为2~3 cm/样品^[13]; 135.8 m崇测冰芯从13.2 m深度至底部共采集了1301个样品, 采样分辨率为~10 cm/样品. 因58.8和135.8 m崇测冰芯钻取点位置仅相距~2 m, 本文直接将58.8 m崇测冰芯0~13.2和135.8 m崇测冰芯的13.2 m至底部的稳定同位素数据(具体数据见表S2和S3)合并成一条序列, 结果如图2所示.

古里雅冰芯分析了12628个稳定同位素样品(分辨率~2.4 cm/样品)^[6], 但目前从NOAA数据库仅能下载10 m(0~100 m深度范围内, 下同), 5 m(100~150 m), 3 m(150~252 m), 1 m(252~308 m)和0.6 m(308~308.6 m)的

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图1 目前已提供底部绝对年代信息的青藏高原冰芯钻取点位置示意图。除古里雅冰芯外, 其他冰芯下面的数字是各自冰芯测量到的最大 ^{14}C 标定年龄, 崇测冰芯下面括号里的数字是应用冰川 2p 模型获得的冰-岩界面处年龄^[5]

Figure 1 Sketch map showing the locations of ice core drilling sites. The numbers for each site except Guliya are the measured oldest ^{14}C ages, while the number inside the bracket below the Chongce site is the estimated ice age at the ice-bedrock contact^[5]

图2 古里雅冰芯(a)和崇测冰芯(b)的 $\delta^{18}\text{O}$ 剖面。崇测冰芯灰线为原始数据, 红线为与古里雅冰芯已发表 $\delta^{18}\text{O}$ 剖面^[6]保持相对步长一致情况下的平均值线。崇测冰芯 ^{14}C 标定年龄来自文献^[5]

Figure 2 The $\delta^{18}\text{O}$ profiles of the Guliya (a) and Chongce (b) ice cores, plotted against their respective depth. The grey line of the Chongce profile stands for the original dataset, while the red line for the averages to match the temporal resolution of the published Guliya record^[6]. The ^{14}C calibrated ages of the Chongce ice core are from Ref. [5]

$\delta^{18}\text{O}$ 平均值(图2)。因为古里雅和崇测冰芯的深度分别为308.6和135.8 m,故按古里雅冰芯的不同深度范围及其相应的平均值步长乘以135.8/308.6后,计算崇测冰芯的相应值,比如对应古里雅冰芯0~100 m深度范围内的10 m平均值,则对崇测冰芯0~100×135.8/308.6 m深度范围内计算每10×135.8/308.6 m平均值。如图2所示,古里雅冰芯和崇测冰芯 $\delta^{18}\text{O}$ 剖面的总体特征具有较好的一致性。进一步对古里雅冰芯和崇测冰芯相对应的 $\delta^{18}\text{O}$ 平均值进行相关分析,得到 $r=0.57(n=110, P<0.001)$,表明二者是显著正相关的。

考虑山区降水的空间差异性显著,以及冰帽不同位置降水沉积过程、粒雪化和成冰过程等的差异,即使两支冰芯的年代范围完全一致,其深度—年代对应关系也不可能完全一致,比如古里雅冰芯100 m深度与崇测冰芯100×135.8/308.6 m深度的年代只能是大体对应,所以优化处理方案是基于二者稳定同位素剖面特征进行摆动匹配(wiggle-matching)^[14,15],比如古里雅冰芯266 m与崇测冰芯110 m深度以下的 $\delta^{18}\text{O}$ 均急剧升高并一直保持在较高水平,故可将这两个深度的 $\delta^{18}\text{O}$ 进行匹配。遗憾的是由于缺乏古里雅冰芯的高分辨率稳定同位素原始数据,

无法进行两支冰芯 $\delta^{18}\text{O}$ 剖面的详细匹配,但不管如何,两支冰芯的 $\delta^{18}\text{O}$ 仍存在显著的正相关性($r=0.57, n=110, P<0.001$),表明古里雅冰芯与崇测冰芯的年代范围应该类似。若果如此,从崇测冰芯年代范围仅囿于全新世时间尺度内^[5]来推断,古里雅冰芯原始定年结果(>500 ka)可能比实际值高估了~2个量级,远大于Cheng等人^[8]所推断的2倍左右。

古里雅冰芯 $\delta^{18}\text{O}$ 剖面(图2(a))的若干特征也不支持其原始定年结果。比如266 m深度(对应~110 ka^[6])至290 m深度(对应~500 ka^[6])范围内的 $\delta^{18}\text{O}$ 均处于较高水平(与指示现代气候状况的古里雅冰芯顶部的 $\delta^{18}\text{O}$ 相当),而110~500 ka时间范围内历经了多次冰期-间冰期循环,上述循环无一例外没有被古里雅冰芯266~290 m深度范围内的 $\delta^{18}\text{O}$ 剖面记录在案(图2(a))。一种极端的可能解释是266 m深度以下的 $\delta^{18}\text{O}$ 剖面仅仅记录了间冰期气候特征,或者另一种极端的可能解释是由于古里雅冰芯钻取点底部位于凹陷区^[16],特别老的冰(“死冰”)也许刚好保存在冰芯钻取点位置,但无论哪种解释均需要更多的证据支持,而且即使上述极端情况能够成立,古里雅冰芯的原始深度-年代关系也仍然需要加以修正。

Thompson等人^[2]曾根据古里雅冰芯与其他青藏高原冰芯年代的显著差异(图1),认为青藏高原冰川作用存在空间异时性。如果古里雅冰芯和崇测冰芯的年代范围基本一致(图2),则显然以往所依赖的空间异时性证据不再有效,因而需要寻找更多的证据进一步探讨青藏高原冰川作用的空间异时性问题。

古里雅冰芯记录自1997年发表后^[6],得到了大量的引用(如2019年5月13日Google Scholar引用检索结果为1001次),被认为是青藏高原古气候重建结果的经典曲线之一。因此,迫切需要更多的证据进一步探究古里雅冰芯以及其他青藏高原冰芯的年代问题。田立德等人^[17]认为冰芯的定年技术,特别是绝对定年技术仍需发展,一些有前景的定年技术可能会应用于冰芯定年工作,比如对崇测冰芯成功进行的¹⁴C测年工作^[5]证实了这一论断。2015年9~10月在1992年古里雅冰芯钻取点位置再次钻取了一支透底冰芯,同时在古里雅冰帽顶点位置钻取了3支透底冰芯,并计划测量这些新钻取古里雅冰芯的¹⁴C, ³⁶Cl, ¹⁰Be, ⁴⁰Ar/³⁸Ar和气泡内氧气的 $\delta^{18}\text{O}$ 等^[18],以期确立其准确年代框架。期待2015年古里雅新冰芯的年代研究结果,以及1992年古里雅冰芯的原始数据能够尽快分享于众。

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补充材料

- 表 S1** 崇测 135.8 m 冰芯的 ^{14}C 原始数据
表 S2 崇测 58.8 m 冰芯 0–13.2 m 的稳定同位素($\delta^{18}\text{O}$)原始数据
表 S3 崇测 135.8 m 冰芯 13.2 m 至底部的稳定同位素($\delta^{18}\text{O}$)原始数据

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Summary for “青藏高原冰芯有多老?”

How old are the Tibetan ice cores?

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Tibetan ice cores provide a wealth of information for past climatic and environmental conditions at different time scales. An accurate chronology is the essential first step and serves as the foundation for ice core research. However, dating ice cores drilled from high-elevation glaciers is always challenging, because seasonal signals used for annual layer counting become unidentifiable in the deeper (older) ice core sections due to rapid thinning of ice layers, and horizons with an identified absolute age are rare. In 1992, a 308.6 m ice core to bedrock was recovered from the Guliya ice cap in the west Kunlun Mountains on the northwestern Tibetan Plateau (TP). The Guliya ice core record has been widely cited (1001 times from the Google Scholar on 13 May 2019) since its publication in 1997. The ice at the depth of 290 m of the Guliya ice core was suggested to be more than 500 ka (thousand years). However, the age ranges of all other Tibetan ice cores (e.g. Dasuopu, East Rongbuk, Puruogangri and Dunde) fall within the Holocene. In 2012 and 2013, four ice cores to bedrock (216.6, 208.6, 135.8 and 133.8 m in length, respectively) were recovered from the Chongce ice cap ~30 km from the Guliya ice core drilling site. The Chongce ice core depth-age relationship was established by a two-parameter flow model calibrated by the ^{14}C , ^{210}Pb , tritium and β -activity measurements. The results suggest that Chongce ice cores are likely of Holocene origin, consistent with other Tibetan ice cores except Guliya. A direct comparison of the depth profiles of stable isotopic between the Chongce and Guliya ice cores shows similar temporal patterns, and a highly significant positive correlation between the two profiles. These results seem to suggest that the Chongce and Guliya ice cores might be similar in age. Therefore, the original chronology of the Guliya ice core might be overestimated by ~2 orders of magnitude. This would further cast doubts on the previous climate reconstructions from the Guliya ice core, as well as the suggested asynchronous glaciation on the Tibetan Plateau based on the original Guliya chronology. In 2015, a new Guliya ice core to bedrock (309.73 m in length) was recovered close to the location of the 1992 Guliya core drilling site. Multiple measurements (including ^{14}C , ^{36}Cl , ^{10}Be , $\delta^{18}\text{O}$ of air in bubbles, and argon isotopic ratios) are planned for this new 2015 Guliya ice core in order to determine its age. Undoubtedly, such new research on the 2015 Guliya ice core is extremely important to resolve the huge discrepancy between the age ranges of the 1992 Guliya ice core and all other Tibetan ice cores.

Tibetan Plateau, ice cores, chronology, Holocene

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