古新世-始新世极热事件碳循环研究进展

陈祚伶^{1,2}

1. 中国科学院地质与地球物理研究所, 中国科学院新生代地质与环境重点实验室, 北京 100029;

2. 中国科学院生物演化与环境卓越创新中心, 北京 100044

E-mail: chenzl@mail.iggcas.ac.cn

2021-07-02 收稿, 2021-08-19 修回, 2021-08-24 接受, 2021-09-09 网络版发表

中国科学院B类战略性先导科技专项(XDB26000000)、国家自然科学基金(41772175)、中国科学院青年创新促进会(2020066)和中国科学院地质与地球物理研究所重点部署项目(IGGCAS-201905)资助

摘要 发生在古新世-始新世界线附近(~56 Ma)、由巨量轻碳注入到海气系统引发的一次快速增温事件被称为古新世-始新世极热事件(PETM)。该事件发生期间的碳释放过程与当前人类燃烧化石燃料向大气中排放CO₂非常相似, 因此对该事件的深入分析可为理解碳排放与气候变化的关系提供地质参考, 同时有助于定量评估自然背景下生态系统、海洋和岩石圈的固碳潜力和速率。根据最新研究成果, 对该事件的碳循环过程进行系统总结和分析, 得到三点初步认识: (1) PETM时期巨量轻碳的释放是响应于事件前期增温的一个正反馈过程, 说明巨量碳的来源可能是大陆坡水合物分解或高纬冻土消融; (2) PETM时期碳释放的平均速率要比现今人类活动的碳排放速率低一个数量级, 暗示人类活动可能触发地球表层系统的正反馈过程, 加剧全球变暖; (3) CO₂的施肥效应和海洋“生物泵”效率的提高加快事件的回返。

关键词 早始新世, 极热事件, 碳循环, 古新世-始新世极热事件

古新世-始新世极热事件(Paleocene-Eocene Thermal Maximum, PETM; ~56 Ma)发生在早新生代长期增温背景下^[1], 为历时极端短暂的快速增温和大规模海洋底栖生物灭绝事件(图1)^[2-4]。事件发生期间, 海陆环境和生态系统发生了显著的改变, 包括全球增温^[5]、海水缺氧^[6,7]、水循环加快^[8]、奇蹄蹄和灵长目动物的出现^[9,10]以及陆生脊椎动物跨大陆迁徙^[11]等。

三方面的地质证据表明, 该事件是由巨量轻碳快速注入到海洋-大气系统所引发。一是海相和陆相各种沉积载体记录的-2‰~-7‰的碳同位素负漂(CIE)。由于海洋、陆地生物圈和大气圈碳库进行充分交换的时间约数千年, 因此在千年时间尺度上可将这3个子碳库看成一个整体, 即可交换碳库, 其碳同位素组成约为-2.27‰(图2)。根据简单的质量平衡方程, 要使可交换

碳库发生大幅度的碳同位素负漂, 必须要有10³ Gt(1 Gt=10¹⁵ g)量级的轻碳快速注入才能实现^[12]; 二是海洋酸化^[13,14]和海洋碳酸盐补偿深度显著变浅^[15], 这些现象与巨量CO₂的加入非常一致; 三是增加的CO₂浓度通过温室效应导致全球地表平均增温~5°C^[5]。由于PETM时期碳的释放过程与现今人类燃烧化石燃料向海气系统排放CO₂非常相似, 因此对该事件的研究具有非常重要的现实意义。对该事件的深入研究有助于理解碳排放与气候变化的关系, 同时有助于定量评估自然背景下生态系统、海洋和岩石圈的固碳潜力和速率。在过去20多年中, 国际学术界对该事件开展了大量的研究, 取得很多成果的同时, 争议也很大, 特别是涉及巨量碳的来源、释放量及碳的归宿方面。本文将综述这些方面的研究进展。

引用格式: 陈祚伶. 古新世-始新世极热事件碳循环研究进展. 科学通报, 2022, 67: 1704-1714

Chen Z L. Carbon-cycle dynamics during the Paleocene-Eocene Thermal Maximum (in Chinese). Chin Sci Bull, 2022, 67: 1704-1714, doi: [10.1360/TB-2021-0652](https://doi.org/10.1360/TB-2021-0652)

图1 (网络版彩色)早新生代(a)和PETM事件(b)碳、氧同位素记录^[1,4]

Figure 1 (Color online) Carbon and oxygen isotope records during the Early Eocene (a) and the PETM (b)^[1,4]

图2 (网络版彩色)可交换碳库储量及同位素组成^[12]. M_b 、 M_a 、 M_o 和 M_t 分别表示生物圈、大气圈、海洋和可交换碳库的碳储量; $\delta^{13}C_b$ 、 $\delta^{13}C_a$ 、 $\delta^{13}C_o$ 和 $\delta^{13}C_t$ 分别代表相应碳库的碳同位素组成

Figure 2 (Color online) Mass and carbon isotope composition of exchangeable carbon reservoirs^[12]. M_b , M_a , M_o , M_t , $\delta^{13}C_b$, $\delta^{13}C_a$, $\delta^{13}C_o$, and $\delta^{13}C_t$ are the masses and $\delta^{13}C$ of carbon in the biosphere, atmosphere, ocean, and exchangeable carbon reservoirs, respectively

1 PETM事件的发生机制及碳源

目前,关于巨量轻碳的来源,争议非常大,主要有以下几种说法:(1)海底天然气水合物的热分解^[12,16].晚古新世,海底大陆坡沉积了 10^4 Gt C 量级生物成因的天然气水合物($\delta^{13}C \sim -55\text{‰}$)^[17],这些水合物对温压条件非常敏感,如果气候环境的变化导致其中10%的释放,就足以引起可交换碳库 $\delta^{13}C$ 显著负漂。(2)泥炭燃烧。

该假说由Kurtz等人^[18]提出,他们认为在古新世-始新世界线附近,全球气候较为干旱,致使当时存在的大量泥炭发生燃烧,并释放出巨量 $\delta^{13}C$ 为 $\sim -22\text{‰}$ 的碳到海气系统,导致该事件的发生。(3)高纬地区冻土层有机质的热分解.利用生物圈生态系统模型,DeConto等人^[19]提出环北极和南极地区永久冻土层有机物($\delta^{13}C \sim -30\text{‰}$)的热分解来解释巨量碳的来源。(4)火山去气^[20].基于B同位素重建结果,并结合地球系统模型模拟, Gutjahr

等人^[20]提出北大西洋火成岩省岩浆活动的去气过程是PETM时期巨量碳的来源($\delta^{13}\text{C} \sim -7\text{‰}$)。 (5) 富有机质沉积地层的接触热变质^[21,22]。 挪威海Vøring盆地岩浆岩脉锆石U-Pb定年表明,大规模的岩浆活动与PETM事件的发生在时间上是接近的^[23],而岩浆活动侵入到富含有机质的沉积地层中可产生大量的热变质成因甲烷($\delta^{13}\text{C} \sim -35\text{‰}$)。 Svensen等人^[21]曾在挪威海的两个沉积盆地中,用地震波图像识别出数千条深约100~300 m的热水通道复合体,估计它们的总面积在8万平方公里以上,并推测可产生300~3000 Gt C的热成因 CH_4 ,其发生年代在55 Ma左右。 (6) 富 ^{12}C 的彗星撞击地球^[24,25]。 Kent等人^[24]发现PETM时期大西洋钻孔沉积物中出现大量富含铁的磁性颗粒,同时伴随铱(Ir)异常。 基于这些事实,他们认为一颗直径为9~10 km的富 ^{12}C 彗星撞击地球足以引起PETM事件^[24,26,27]。 以上前3种观点强调气候系统的内在反馈过程导致事件的发生,即表生碳循环-气候系统达到某种阈值,巨量 CO_2 被释放;而后3种观点则强调事件的突发性,即随机性过程导致了极热事件的发生。 争议的焦点在于: (1) PETM是一个孤立事件还是众多相似事件中的一个特例? (2) 碳同位素记录的精细结构特征及其与气候环境之间的耦合关系?

来自深海钻孔和陆相地层的沉积记录显示,在早

始新世(56~52 Ma)长期持续增温背景下^[1],地球气候系统发生了一系列包括PETM在内的历时短暂的(<200 ka)快速增温事件^[4,28,29]。 我们曾从抚顺盆地陆相煤系地层中识别出早始新世4次极热事件,通过同海相沉积记录对比,发现海陆记录的碳同位素负漂幅度差异与海洋碳酸盐CIE呈现显著的线性相关,暗示这些极热事件很可能是同一碳源重复性注入所致^[29],表明PETM事件不大可能是一次独一无二的随机事件。 天文调谐结果显示,早始新世极热事件的发生与轨道偏心率最大值在时间上是一致的,因此部分学者提出天文驱动触发了气候系统的内在反馈,从而导致极热事件的发生^[19,30,31]。 但最近一些研究却发现,PETM事件与偏心率最大值时期并不一致^[4,32,33]。 由此可见,这些事件是否受天文因素共同控制还有赖于新证据的获得。

PETM事件的一个显著特点是大幅度的碳同位素负漂,其精细结构特征及其与环境变化之间的耦合关系是约束事件发生机制和碳源的关键。 在地质记录上,碳同位素负漂表现为一个低谷,根据曲线形状,可将其划分为3个时段:“负漂期”、“核心期”和“回返期”(图3)。 典型的“负漂期”结构主要有3种:一是以意大利Forada露头剖面碳酸盐碳同位素记录为代表的“单次快速负漂”^[34];二是以ODP 690钻孔全岩碳酸盐碳同位素记录

图3 (网络版彩色)PETM事件碳同位素负漂的典型结构。数据来源: Forada剖面数据^[34]、ODP 690钻孔数据^[35]、Bighorn盆地数据^[36]

Figure 3 (Color online) Typical structure of carbon isotope excursion during the PETM. Data source: Forada section^[34], ODP 690 core^[35], and Bighorn Basin core^[36]

为代表的“阶段性负漂”^[35]，三是以Bighorn盆地钙结核碳同位素记录为代表的“两次快速负漂”^[36]。第一种结构特征暗示该事件可能是随机性的灾难性事件，比如富¹²C的彗星撞击地球；而后两种结构特征则说明气候系统的内在反馈过程可能是诱发事件的主因，比如天然气水合物的热分解。造成这些矛盾结果的可能原因是沉积记录的不完整性和低分辨率。深海记录主要受到两方面的制约：一是典型的深海沉积厚度只有1~2 m左右，分辨率不高，且很容易受到生物扰动的影响。由于深海碳酸盐主要是由钙质微体化石(<10 μm)构成，生物扰动造成的微体化石的向上混合以及与生物壳体大小相关的生命效应(vital effect)可能导致了ODP 690记录的阶段性变化特征^[37~39]。二是PETM时期，尤其是事件触发期，海洋酸化导致深海大量碳酸盐溶解^[15]，很可能造成“负漂期”碳酸盐信号丢失，记录失真。而Bighorn盆地 $\delta^{13}\text{C}$ 曲线是以古土壤的钙结核为主建立的，分辨率不高，连续性亦差。因此，对事件的细节刻画得不够清楚。最近，我们通过对南阳盆地和抚顺盆地高分辨率陆相碳同位素分析发现，PETM时期碳同位素负漂是一个逐渐缓慢的过程(图4)^[29,40]。同样，在相对湿润的北极地区，海相钻孔高分辨率碳同位素记录也表明CIE的变化是一个渐变的过程^[41]。这些结果暗示巨量轻碳的释放是一个缓慢、持续的过程，而非典型海相沉积记录的“脉冲”式或“灾难”性注入方式^[35,36]。

通过对南阳盆地PETM时期温度的重建^[40]，我们还发现两个比较有意思的现象。一是事件发生过程中，温度的变化趋势与碳同位素负漂是紧密耦合的，说明巨量轻碳的注入与温度的变化是紧密相关的。二是同位素负漂发生前，温度已持续缓慢增加~4°C(图4)。多方面的证据支持显著的环境变化先于CIE发生。ODP 690钻孔碳氧同位素结果显示，在CIE发生之前，浮游有孔虫氧同位素即开始变负，表明PETM事件发生之前海表水温度增加了约2°C^[42]。同样，在Forada地区，CIE发生之前TEX₈₆温标记录了2~3°C的海表升温^[43]。在赤道太平洋和亚热带大西洋区域，底栖有孔虫Mg/Ca温标表明海洋中层水升温发生在CIE之前^[44,45]。基于这一观测结果，Tripathi和Elderfield^[44]认为，PETM事件发生之前，环流格局的变化导致中层水温升高，诱发甲烷水合物分解释放，该机制的一个前提是升温仅限于海洋。随后，通过对新泽西州两个海相剖面 and ODP 959钻孔高分辨率TEX₈₆温标的分析，发现海表水升温先于CIE约数千年^[46,47]。来自北美Bighorn盆地牙釉质氧同位素分析结果似乎也表明了PETM事件发生之前存在增温^[48]。此外，许多研究还表明在PETM事件发生之前，水循环、植物群落和沟鞭藻等也发生了显著的改变^[46,49,50]，这些变化或多或少与事件前的升温有关。综合已有的研究，基本可以得出这样一个结论：碳同位素负漂发生之前，升温是一个全球现象。由于环流格局的变化仅能

图4 (网络版彩色)PETM事件的陆相高分辨率碳同位素和温度记录^[29,40]

Figure 4 (Color online) High-resolution terrestrial carbon isotope and temperature records for the PETM^[29,40]

导致部分水体的升温,却难以解释大陆温度的变化,因此其不大可能是PETM事件的触发机制.对比南阳盆地温度变化与碳同位素记录,我们发现在事件前期增温过程中,碳同位素并没有发生明显变化.由于晚古新世大气CO₂的 $\delta^{13}\text{C}$ 值为 $\sim -5\text{‰}$ ^[51],与幔源物质的碳同位素组成($-5\text{‰}\sim -7\text{‰}$)大致相当^[46].这些结果说明存在这样一种可能:如果同位素负漂前的升温是由大气CO₂浓度增加所致,那么这些CO₂应来源于火山去气^[52,53].

综上,对该事件大体上有三点认识:(1) PETM事件并非独一无二,而是众多事件中的一个特例;(2)“负漂期”碳同位素整体上表现为一个逐步、缓慢的持续变负过程;(3)事件发生期间,温度和碳同位素的变化是紧密耦合的,而事件发生前存在一个持续增温的过程.这些观测结果为理解该事件碳排放过程提供了一个基本约束:巨量轻碳的释放是响应于前期增温的一个正反馈过程,潜在的碳源包括海底天然气水合物和冻土有机质.最近,McKay和Lenton^[54]对早新生代海洋碳酸盐碳氧同位素进行系统地集成分析,发现随着晚古新世长期持续的缓慢增温,碳循环系统“韧性”逐渐减弱,也就是碳循环系统不稳定性增加,对外在扰动的敏感性增强,容易突破系统的临界点(tipping point).年代学结果表明,北大西洋火山岩省在62~58 Ma期间异常活跃^[55,56],其总面积为 $1.3\times 10^6\text{ km}^2$,总体积可达 $10\times 10^6\text{ km}^3$,当时可能释放了大量地幔来源的CO₂.基于此,可推论整个事件的可能情景为:晚古新世北大西洋火山岩省的剧烈活动以火山去气的方式向大气中注入大量CO₂,通过温室驱动导致全球范围的持续升温,使碳循环系统不稳定性增加,最终突破系统临界点,诱发巨量还原性碳库(天然气水合物、冻土)分解释放,导致快速增温,开启轻碳分解释放-增温的正反馈过程.由于温度峰值持续过程非常短,且与 $\delta^{13}\text{C}$ 最小值是非常吻合的(图4),在一定程度上可能表明还原性碳库被消耗殆尽,最终导致正反馈过程的终止.

2 PETM时期碳排放量和排放速率

在PETM开始阶段,究竟有多少CO₂被释放到海洋-大气系统中,其排放速率有多快,迄今尚无明确答案.有关该时期总碳排放量的估算,主要有两种方法.

第一种方法是基于质量平衡方程进行估算.由于PETM事件的持续时间(120~200 ka)远大于表生系统碳循环交换时间(10 ka)^[57],因此在研究这一事件时,可把整个外生碳库视为一个可交换碳库整体(M_t)(图2).根

据质量平衡原理,可以得到简化后的方程为

$$(M_t + M_r)(\delta^{13}\text{C}_t') = M_t(\delta^{13}\text{C}_t) + M_r(\delta^{13}\text{C}_r), \quad (1)$$

式中, $\delta^{13}\text{C}_t'$ 代表巨量轻碳(M_r)注入海-气系统后可交换碳库的碳同位素组成.

进一步得出碳排放量估算方程:

$$M_r = M_t(\text{CIE}) / (\delta^{13}\text{C}_r - \delta^{13}\text{C}_t - \text{CIE}). \quad (2)$$

从方程(2)不难看出,碳排放量(M_r)主要受负漂幅度(CIE)和碳源碳同位素组成($\delta^{13}\text{C}_r$)的制约.遗憾的是,目前学术界对PETM时期可交换碳库的真实CIE幅度存在较大的分歧.根据已发表的数据,海相各沉积载体记录的CIE幅度为 $-2\text{‰}\sim -4\text{‰}$,而陆相各种沉积载体记录的CIE幅度为 $-5\text{‰}\sim -6\text{‰}$ ^[58],两者相差近3‰.根据理论模型,排放到大气中的CO₂在千年时间尺度即可与海水达到平衡^[59],因此海陆记录的CIE幅度应该大致相当.而两者之间显著的差异可能来自两方面的原因:一是PETM时期海洋酸化可导致记录的CIE幅度偏小.一方面酸化导致海底碳酸盐大量溶解,会释放 $\delta^{13}\text{C}$ 值相对偏正的碳到海水中,另一方面可通过溶解作用溶蚀掉部分沉积物,尤其是碳同位素达最负值时期,致使真实的最负值并未被记录到,即所谓的“截断效应”^[60].二是PETM时期大气相对湿度、植物群落和大气CO₂浓度的变化会导致植物光合作用过程中碳同位素分馏的改变,可能放大了陆相载体记录的CIE幅度^[61~64].Diefendorf等人^[65]基于大数据分析得到的统计方程,通过校正植物群落和气候变化对分馏值的影响,计算出PETM时期可交换碳库的真实CIE幅度约为 -4.6‰ .该值与Erling等人^[66]利用海洋古菌脂类生标分析得到的结果基本一致.利用方程(2),要使可交换碳库发生 -4.6‰ 的碳同位素负漂,至少需要 $\sim 4000\text{ Gt C}$ 的天然气水合物或 8400 Gt C 的冻土分解才能实现.

第二种方法是结合地质记录和数值模拟进行估算.根据Zachos等人^[15]的研究,PETM时期,南大洋CCD(calcite compensation depth)上升了2000多米,据模式计算至少需要 4500 Gt C 的加入才能够实现.Zeebe等人^[67]以CCD变化和碳同位素组成的观测数据为约束,利用简单的碳循环模型估算出PETM时期总碳排放量约为 4500 Gt C .该估算的一个前提是全球海洋CCD均发生了显著的上升,但由于研究数据的缺乏和海洋环流等因素的影响,全球海洋CCD究竟上升了多少,目前尚不清楚.Meissner等人^[68]利用地球系统气候模式计算表

明,至少需要注入7000 Gt C才能解释重建的温度结果。最近, Gutjahr等人^[20]通过对有孔虫壳体B同位素的研究,发现PETM时期海水pH降低了~0.3个单位,根据地球系统模型(cGENIE)估算,至少需要10000 Gt C注入到海-气系统才能实现。

总之,目前对PETM时期碳释放量的估算变化范围非常大,在4000~10000 Gt C之间。要准确获得当时有多少碳加入到大气-海洋系统中,还需多方面的数据加以制约,如当时大气CO₂浓度背景、大洋的温度背景、陆地生物圈的碳储量、大洋的酸碱度、CO₂释放阶段的时间跨度以及当时碳循环的速率等。只有在大量研究数据获得后,结合地球系统模型模拟计算,才能获得逼近真实情况的估算值。

在获得总碳排放量的条件下,要估算PETM时期的碳排放速率,还需要对“负漂期”的持续时间加以约束。目前,主要有两种方法来建立PETM事件的时间标尺:轨道-旋回地层学^[69]和³He时标^[70]。两种方法重建的“负漂期”持续时间差别较大,从10~30 ka不等^[33,71,72]。结合碳排放量的估算,可获得PETM时期平均碳排放速率的大致范围为0.15~1 Gt C/a,这比当前人类活动的碳排放速率(~10 Gt C/a)^[73]要小一个数量级。由于人类排放导致温室气体浓度的快速增加,全球气候系统通过辐射强迫将具有远快于PETM时期的增温潜力,很可能突破碳循环系统的临界阈值,诱发还原碳库分解-增温这一正反馈过程,加速全球变暖。

3 碳消耗机制及归宿

从碳同位素曲线来看, PETM事件大致分为3个阶段。首先是 $\delta^{13}\text{C}$ 快速负漂,然后是在一段时间内保持低值,最后是 $\delta^{13}\text{C}$ 值呈指数形式变正,逐渐达到事件发生前的数值。第三阶段代表了巨量轻碳的消耗吸收过程。这种消耗过程是通过什么机制完成的? 巨量轻碳的最终归宿在哪里? 对这些问题的研究,有助于定量评估自然背景下各圈层的固碳潜力和速率,为我国通过“基于自然的解决方案”实现碳减排并于2060年实现碳中和目标提供理论依据和科学支撑。目前,关于PETM“回返期”巨量轻碳的消耗机制,最流行的一种观点是土壤硅酸盐风化作用对CO₂的消耗^[58],其具体机制为两个:一是在温度升高的情况下,全球水循环加快^[8,61],使土壤风化速率加强,导致由河流带到海洋的CO₃²⁻离子量增加,促使更多的CaCO₃在海洋中沉淀,从而消耗CO₂。二是在大气CO₂分压增加的条件下,土壤的呼吸作用增

强,导致土壤内部CO₂的分压增加,土壤pH下降,从而促使化学风化加强。这两个机制都强调土壤硅酸盐的风化作用,只不过前者以湿度增加为出发点,后者以酸度增加为出发点。在PETM时期,高岭石含量的增加^[74,75]、化学风化指数的升高^[75,76]以及海洋Os同位素的显著正漂^[77],均表明该时期风化作用确实得到加强。而事件“回返期”CCD快速加深并低于事件发生前的水平^[78,79],也进一步说明巨量碳通过加强的风化最终以碳酸盐的形式被储存于深海。然而,根据理论模型计算,巨量碳释放后,仅通过硅酸盐风化,大约需要100 ka才能回返到事件发生前的水平^[80]。最新的研究结果却表明, PETM事件碳同位素从最低值回返到接近背景的水平,用了不到40 ka的时间^[81]。理论模型与地质记录之间的不吻合说明地球系统存在其他负反馈机制来加快轻碳的吸收。

两种潜在的过程可能加快了“回返期”轻碳的吸收。第一种机制涉及陆地生态系统的固碳作用,体现在两个方面。一是PETM时期高浓度的大气CO₂对植物的施肥效应,导致初级生产力增加的同时提高光合作用产物的C/N比值,增加土壤有机质的抗降解能力,最终促使陆地生物圈和土壤碳储量的增加^[81]。二是PETM时期高低纬度温度梯度减小^[82],导致气候带向两极移动,热带植被和湿地向高纬扩张^[83],增加陆地生物圈的碳储量。根据模式计算,在综合考虑CO₂的施肥效应和陆生植被的扩张条件下, PETM时期陆地生物圈的固碳潜力可达1210 Gt C^[84]。第二种机制涉及海洋“生物泵”效率的增加,即海洋表层生物输出生产力的提高。PETM时期大陆风化加强,大量N、P和Fe等营养物质以径流方式输送到海洋,势必会刺激海洋输出生产力的增加。根据Ma等人^[85]对全球海洋生物成因Ba通量的研究, PETM时期,海洋输出生产力相对事件发生前提近了3倍。在北冰洋和北大西洋海岸带,有机碳沉积通量在PETM时期增加了一个数量级^[86,87],说明海洋输出生产力的增加及随后的有机碳埋藏固定了大量的轻碳。基于Komar和Zeebe^[88]的研究,只有在考虑P通量增加促使“生物泵”效率显著提高的条件下,模型模拟结果才能与地质记录最为吻合。不难看出,地球表层系统的碳循环过程具有自我调节和修复的功能。随着当前人类碳排放导致的持续增温,海洋“生物泵”的效率可能持续增强,具有较大的潜力来吸收大气中过量的CO₂。

尽管以上机制均表明了吸收CO₂的潜力,但每一个过程在事件“回返期”固碳所占的权重并不清楚,仍需

要更多的地质数据,并结合数值模拟来加以约束.

4 总结与启示

本文通过对PETM时期碳循环过程的系统总结和梳理,对事件的发生机制、碳源、碳排放量和回返过程得到如下初步结论.

(1) PETM事件的发生是响应于事件前期增温的一个正反馈过程,说明巨量的碳来源于地球表层的还原碳库,可能的碳源包括天然气水合物和冻土有机质.

(2) PETM时期碳排放量在4000~10000 Gt C之间,平均碳排放速率为0.15~1 Gt C/a,变化范围非常大,仍需获取大量的地质数据,并结合数值模拟来加以约束.

(3) 陆生植被的扩张、CO₂的施肥效应和海洋“生

物泵”效率的提高加快了轻碳的吸收,是PETM事件快速回返的主因.

鉴古知今,当前人类活动正以燃烧化石燃料等方式向大气中注入大量的CO₂,其排放过程与PETM时期碳排放非常相似,但排放速率(~10 Gt C/a)远高于PETM时期碳排放速率.由于人类排放导致温室气体浓度的快速增加,全球气候系统通过辐射强迫将具有远快于PETM时期的增温潜力,很可能诱发海底天然气水合物等还原碳库的大量分解,形成正反馈,加剧全球变暖.因此,为了避免甲烷水合物分解-增温这一潜在正反馈的开启,以及伴随的巨大环境扰动,人类应加强各洋盆大陆坡水合物的监测,同时控制温室气体的排放.

参考文献

- Zachos J C, Dickens G R, Zeebe R E. An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. *Nature*, 2008, 451: 279–283
- Kennett J P, Stott L D. Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Palaeocene. *Nature*, 1991, 353: 225–229
- Koch P L, Zachos J C, Gingerich P D. Correlation between isotope records in marine and continental carbon reservoirs near the Palaeocene/Eocene boundary. *Nature*, 1992, 358: 319–322
- Zachos J C, McCarren H, Murphy B, et al. Tempo and scale of late Paleocene and early Eocene carbon isotope cycles: Implications for the origin of hyperthermals. *Earth Planet Sci Lett*, 2010, 299: 242–249
- Dunkley Jones T, Lunt D J, Schmidt D N, et al. Climate model and proxy data constraints on ocean warming across the Paleocene-Eocene Thermal Maximum. *Earth-Sci Rev*, 2013, 125: 123–145
- Dickson A J, Rees-Owen R L, März C, et al. The spread of marine anoxia on the northern Tethys margin during the Paleocene-Eocene Thermal Maximum. *Paleoceanography*, 2014, 29: 471–488
- Yao W, Paytan A, Wortmann U G. Large-scale ocean deoxygenation during the Paleocene-Eocene Thermal Maximum. *Science*, 2018, 361: 804–806
- Carmichael M J, Inglis G N, Badger M P S, et al. Hydrological and associated biogeochemical consequences of rapid global warming during the Paleocene-Eocene Thermal Maximum. *Geochem Geophys Geosyst*, 2017, 157: 114–138
- Gingerich P D. Mammalian responses to climate change at the Paleocene-Eocene boundary: Polecat Bench record in the Northern Bighorn Basin, Wyoming. In: Wing S L, Gingerich P D, Schmitz B, et al., eds. *Causes and Consequences of Globally Warm Climates in the Early Paleogene*. Boulder: Geological Society of America, 2003. 463–478
- Gingerich P D. Environment and evolution through the Paleocene-Eocene Thermal Maximum. *Trends Ecol Evol*, 2006, 21: 246–253
- Smith T, Rose K D, Gingerich P D. Rapid Asia-Europe-North America geographic dispersal of earliest Eocene primate *Teilhardina* during the Paleocene-Eocene Thermal Maximum. *Proc Natl Acad Sci USA*, 2006, 103: 11223–11227
- Dickens G R, O'Neil J R, Rea D K, et al. Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene. *Paleoceanography*, 1995, 10: 965–971
- Penman D E, Hönisch B, Zeebe R E, et al. Rapid and sustained surface ocean acidification during the Paleocene-Eocene Thermal Maximum. *Paleoceanography*, 2014, 29: 357–369
- Babila T L, Penman D E, Hönisch B, et al. Capturing the global signature of surface ocean acidification during the Palaeocene-Eocene Thermal Maximum. *Phil Trans R Soc A*, 2018, 376: 20170072
- Zachos J C, Röhl U, Schellenberg S A, et al. Rapid acidification of the ocean during the Paleocene-Eocene Thermal Maximum. *Science*, 2005, 308: 1611–1615
- Dickens G R. Down the Rabbit Hole: Toward appropriate discussion of methane release from gas hydrate systems during the Paleocene-Eocene Thermal Maximum and other past hyperthermal events. *Clim Past*, 2011, 7: 831–846

- 17 Gu G, Dickens G R, Bhatnagar G, et al. Abundant Early Palaeogene marine gas hydrates despite warm deep-ocean temperatures. *Nat Geosci*, 2011, 4: 848–851
- 18 Kurtz A C, Kump L R, Arthur M A, et al. Early Cenozoic decoupling of the global carbon and sulfur cycles. *Paleoceanography*, 2003, 18: 1090
- 19 DeConto R M, Galeotti S, Pagani M, et al. Past extreme warming events linked to massive carbon release from thawing permafrost. *Nature*, 2012, 484: 87–91
- 20 Gutjahr M, Ridgwell A, Sexton P F, et al. Very large release of mostly volcanic carbon during the Palaeocene-Eocene Thermal Maximum. *Nature*, 2017, 548: 573–577
- 21 Svensen H, Planke S, Mølne-Sørensen A, et al. Release of methane from a volcanic basin as a mechanism for initial Eocene global warming. *Nature*, 2004, 429: 542–545
- 22 Frieling J, Svensen H H, Planke S, et al. Thermogenic methane release as a cause for the long duration of the PETM. *Proc Natl Acad Sci USA*, 2016, 113: 12059–12064
- 23 Svensen H, Planke S, Corfu F. Zircon dating ties NE Atlantic sill emplacement to initial Eocene global warming. *J Geol Soc*, 2010, 167: 433–436
- 24 Kent D V, Cramer B S, Lanci L, et al. A case for a comet impact trigger for the Paleocene/Eocene Thermal Maximum and carbon isotope excursion. *Earth Planet Sci Lett*, 2003, 211: 13–26
- 25 Schaller M F, Fung M K, Wright J D, et al. Impact ejecta at the Paleocene-Eocene boundary. *Science*, 2016, 354: 225–229
- 26 Cramer B S, Kent D V. Bolide summer: The Paleocene/Eocene Thermal Maximum as a response to an extraterrestrial trigger. *Palaeogeogr Palaeoclimatol Palaeoecol*, 2005, 224: 144–166
- 27 Wright J D, Schaller M F. Evidence for a rapid release of carbon at the Paleocene-Eocene Thermal Maximum. *Proc Natl Acad Sci USA*, 2013, 110: 15908–15913
- 28 Nicolo M J, Dickens G R, Hollis C J, et al. Multiple early Eocene hyperthermals: Their sedimentary expression on the New Zealand continental margin and in the deep sea. *Geology*, 2007, 35: 699–702
- 29 Chen Z, Ding Z, Tang Z, et al. Early Eocene carbon isotope excursions: Evidence from the terrestrial coal seam in the Fushun Basin, Northeast China. *Geophys Res Lett*, 2014, 41: 3559–3564
- 30 Lourens L J, Sluijs A, Kroon D, et al. Astronomical pacing of late Palaeocene to early Eocene global warming events. *Nature*, 2005, 435: 1083–1087
- 31 Galeotti S, Krishnan S, Pagani M, et al. Orbital chronology of Early Eocene hyperthermals from the Contessa Road section, central Italy. *Earth Planet Sci Lett*, 2010, 290: 192–200
- 32 Westerhold T, Röhl U, Laskar J, et al. On the duration of magnetochrons C24r and C25n and the timing of early Eocene global warming events: Implications from the Ocean Drilling Program Leg 208 Walvis Ridge depth transect. *Paleoceanography*, 2007, 22: PA2201
- 33 Charles A J, Condon D J, Harding I C, et al. Constraints on the numerical age of the Paleocene-Eocene boundary. *Geochem Geophys Geosyst*, 2011, 12: Q0AA17
- 34 Giusberti L, Rio D, Agnini C, et al. Mode and tempo of the Paleocene-Eocene Thermal Maximum in an expanded section from the Venetian pre-Alps. *Geol Soc Am Bull*, 2007, 119: 391–412
- 35 Bains S, Corfield R M, Norris R D. Mechanisms of climate warming at the end of the Paleocene. *Science*, 1999, 285: 724–727
- 36 Bowen G J, Maibauer B J, Kraus M J, et al. Two massive, rapid releases of carbon during the onset of the Palaeocene-Eocene Thermal Maximum. *Nat Geosci*, 2014, 8: 44–47
- 37 Bralower T J. Evidence of surface water oligotrophy during the Paleocene-Eocene Thermal Maximum: Nannofossil assemblage data from Ocean Drilling Program Site 690, Maud Rise, Weddell Sea. *Paleoceanography*, 2002, 17: 13-1–13-12
- 38 Si W, Aubry M P. Vital effects and ecologic adaptation of photosymbiont-bearing planktonic foraminifera during the Paleocene-Eocene Thermal Maximum, implications for paleoclimate. *Paleoceanogr Paleoclimatology*, 2018, 33: 112–125
- 39 Hupp B N, Kelly D C, Zachos J C, et al. Effects of size-dependent sediment mixing on deep-sea records of the Paleocene-Eocene Thermal Maximum. *Geology*, 2019, 47: 749–752
- 40 Chen Z, Wang X, Hu J, et al. Structure of the carbon isotope excursion in a high-resolution lacustrine Paleocene-Eocene Thermal Maximum record from central China. *Earth Planet Sci Lett*, 2014, 408: 331–340
- 41 Cui Y, Kump L R, Ridgwell A J, et al. Slow release of fossil carbon during the Palaeocene-Eocene Thermal Maximum. *Nat Geosci*, 2011, 4: 481–485
- 42 Thomas D J, Zachos J C, Bralower T J, et al. Warming the fuel for the fire: Evidence for the thermal dissociation of methane hydrate during the Paleocene-Eocene Thermal Maximum. *Geology*, 2002, 30: 1067–1070
- 43 Tipple B J, Pagani M, Krishnan S, et al. Coupled high-resolution marine and terrestrial records of carbon and hydrologic cycles variations during the Paleocene-Eocene Thermal Maximum (PETM). *Earth Planet Sci Lett*, 2011, 311: 82–92
- 44 Tripathi A K, Elderfield H. Abrupt hydrographic changes in the equatorial Pacific and subtropical Atlantic from foraminiferal Mg/Ca indicate

- greenhouse origin for the thermal maximum at the Paleocene-Eocene Boundary. *Geochem Geophys Geosyst*, 2004, 5: Q02006
- 45 Tripathi A, Elderfield H. Deep-sea temperature and circulation changes at the Paleocene-Eocene Thermal Maximum. *Science*, 2005, 308: 1894–1898
- 46 Sluijs A, Brinkhuis H, Schouten S, et al. Environmental precursors to rapid light carbon injection at the Palaeocene/Eocene boundary. *Nature*, 2007, 450: 1218–1221
- 47 Frieling J, Peterse F, Lunt D J, et al. Widespread warming before and elevated barium burial during the Paleocene-Eocene Thermal Maximum: Evidence for methane hydrate release? *Paleoceanogr Paleocl*, 2019, 34: 546–566
- 48 Secord R, Gingerich P D, Lohmann K C, et al. Continental warming preceding the Palaeocene-Eocene Thermal Maximum. *Nature*, 2010, 467: 955–958
- 49 Kender S, Stephenson M H, Riding J B, et al. Marine and terrestrial environmental changes in NW Europe preceding carbon release at the Paleocene-Eocene transition. *Earth Planet Sci Lett*, 2012, 353–354: 108–120
- 50 Alegret L, Reolid M, Vega Pérez M. Environmental instability during the latest Paleocene at Zumaia (Basque-Cantabric Basin): The bellwether of the Paleocene-Eocene Thermal Maximum. *Palaeogeogr Palaeoclimatol Palaeoecol*, 2018, 497: 186–200
- 51 Tipple B J, Meyers S R, Pagani M. Carbon isotope ratio of Cenozoic CO₂: A comparative evaluation of available geochemical proxies. *Paleoceanography*, 2010, 25: PA3202
- 52 Bralower T J, Thomas D J, Zachos J C, et al. High-resolution records of the late Paleocene Thermal Maximum and circum-Caribbean volcanism: Is there a causal link? *Geology*, 1997, 25: 963–966
- 53 Wicczorek R, Fantle M S, Kump L R, et al. Geochemical evidence for volcanic activity prior to and enhanced terrestrial weathering during the Paleocene Eocene Thermal Maximum. *Geochim Cosmochim Acta*, 2013, 119: 391–410
- 54 McKay D I A, Lenton T M. Reduced carbon cycle resilience across the Palaeocene-Eocene Thermal Maximum. *Clim Past*, 2018, 14: 1515–1527
- 55 Storey M, Duncan R A, Swisher C C. Paleocene-Eocene Thermal Maximum and the opening of the northeast Atlantic. *Science*, 2007, 316: 587–589
- 56 Hansen J, Jerram D A, McCaffrey K, et al. The onset of the North Atlantic Igneous Province in a rifting perspective. *Geol Mag*, 2009, 146: 309–325
- 57 Walker J C G, Kasting J F. Effects of fuel and forest conservation on future levels of atmospheric carbon dioxide. *Palaeogeogr Palaeoclimatol Palaeoecol*, 1992, 97: 151–189
- 58 McInerney F A, Wing S L. The Paleocene-Eocene Thermal Maximum: A perturbation of carbon cycle, climate, and biosphere with implications for the future. *Annu Rev Earth Planet Sci*, 2011, 39: 489–516
- 59 Archer D. Fate of fossil fuel CO₂ in geologic time. *J Geophys Res*, 2005, 110: C09S05
- 60 McCarren H, Thomas E, Hasegawa T, et al. Depth dependency of the Paleocene-Eocene carbon isotope excursion: Paired benthic and terrestrial biomarker records (Ocean Drilling Program Leg 208, Walvis Ridge). *Geochem Geophys Geosyst*, 2008, 9: Q10008
- 61 Bowen G J, Beerling D J, Koch P L, et al. A humid climate state during the Palaeocene/Eocene Thermal Maximum. *Nature*, 2004, 432: 495–499
- 62 Schouten S, Woltering M, Rijpstra W I C, et al. The Paleocene-Eocene carbon isotope excursion in higher plant organic matter: Differential fractionation of angiosperms and conifers in the Arctic. *Earth Planet Sci Lett*, 2007, 258: 581–592
- 63 Schubert B A, Hope Jahren A. Reconciliation of marine and terrestrial carbon isotope excursions based on changing atmospheric CO₂ levels. *Nat Commun*, 2013, 4: 1653
- 64 Chen Z, Dong X, Wang X, et al. Spatial change of precipitation in response to the Paleocene-Eocene thermal Maximum warming in China. *Glob Planet Change*, 2020, 194: 103313
- 65 Diefendorf A F, Mueller K E, Wing S L. Global patterns in leaf ¹³C discrimination and implications for studies of past and future climate. *Proc Natl Acad Sci USA*, 2010, 107: 5738–5743
- 66 Elling F J, Gottschalk J, Doeana K D, et al. Archaeal lipid biomarker constraints on the Paleocene-Eocene carbon isotope excursion. *Nat Commun*, 2019, 10: 4519
- 67 Zeebe R E, Zachos J C, Dickens G R. Carbon dioxide forcing alone insufficient to explain Palaeocene-Eocene Thermal Maximum warming. *Nat Geosci*, 2009, 2: 576–580
- 68 Meissner K J, Bralower T J, Alexander K. The Paleocene-Eocene Thermal Maximum: How much carbon is enough? *Paleoceanography*, 2014, 29: 946–963
- 69 Norris R D, Röhl U. Carbon cycling and chronology of climate warming during the Palaeocene/Eocene transition. *Nature*, 1999, 401: 775–778
- 70 Farley K A, Eltgroth S F. An alternative age model for the Paleocene-Eocene Thermal Maximum using extraterrestrial ³He. *Earth Planet Sci Lett*, 2003, 208: 135–148
- 71 Röhl U, Westerhold T, Bralower T J, et al. On the duration of the Paleocene-Eocene Thermal Maximum (PETM). *Geochem Geophys Geosyst*, 2007, 8: Q12002

- 72 Murphy B H, Farley K A, Zachos J C. An extraterrestrial ^3He -based timescale for the Paleocene-Eocene Thermal Maximum (PETM) from Walvis Ridge, IODP Site 1266. [Geochim Cosmochim Acta](#), 2010, 74: 5098–5108
- 73 Le Quéré C, Andrew R M, Canadell J G, et al. Global carbon budget 2016. *Earth Syst Sci Data*, 2016, 8: 605–649
- 74 Robert C, Kennett J P. Antarctic subtropical humid episode at the Paleocene-Eocene boundary: Clay-mineral evidence. [Geology](#), 1994, 22: 211–214
- 75 Chen Z, Ding Z, Yang S, et al. Increased precipitation and weathering across the Paleocene-Eocene Thermal Maximum in central China. [Geochem Geophys Geosyst](#), 2016, 17: 2286–2297
- 76 Khozyem H, Adatte T, Spangenberg J, et al. New geochemical constraints on the Paleocene-Eocene Thermal Maximum: Dababiya GSSP, Egypt. *Palaeogeogr Palaeoclimatol Palaeoecol*, 2005, 429: 117–135
- 77 Dickson A J, Cohen A S, Cohen A S, et al. Evidence for weathering and volcanism during the PETM from Arctic Ocean and Peri-Tethys osmium isotope records. *Geology*, 2015, 438: 300–307
- 78 Luo Y, Boudreau B P, Dickens G R, et al. An alternative model for CaCO_3 over-shooting during the PETM: Biological carbonate compensation. [Earth Planet Sci Lett](#), 2016, 453: 223–233
- 79 Penman D E, Turner S K, Sexton P F, et al. An abyssal carbonate compensation depth overshoot in the aftermath of the Palaeocene-Eocene Thermal Maximum. [Nat Geosci](#), 2016, 9: 575–580
- 80 Dickens G R, Castillo M M, Walker J C G. A blast of gas in the latest Paleocene: Simulating first-order effects of massive dissociation of oceanic methane hydrate. [Geology](#), 1997, 25: 259–262
- 81 Bowen G J, Zachos J C. Rapid carbon sequestration at the termination of the Palaeocene-Eocene Thermal Maximum. [Nat Geosci](#), 2010, 3: 866–869
- 82 Frieling J, Gebhardt H, Huber M, et al. Extreme warmth and heat-stressed plankton in the tropics during the Paleocene-Eocene Thermal Maximum. [Sci Adv](#), 2017, 3: e1600891
- 83 Huurdeman E P, Frieling J, Reichgelt T, et al. Rapid expansion of meso-megathermal rain forests into the southern high latitudes at the onset of the Paleocene-Eocene Thermal Maximum. [Geology](#), 2020, 49: 40–44
- 84 Beerling D J. Increased terrestrial carbon storage across the Palaeocene-Eocene boundary. *Palaeogeogr Palaeoclimatol Palaeoecol*, 2000, 161: 395–405
- 85 Ma Z, Gray E, Thomas E, et al. Carbon sequestration during the Palaeocene-Eocene Thermal Maximum by an efficient biological pump. [Nat Geosci](#), 2014, 7: 382–388
- 86 John C M, Bohaty S M, Zachos J C, et al. North American continental margin records of the Paleocene-Eocene Thermal Maximum: Implications for global carbon and hydrological cycling. *Paleoceanography*, 2008, 23: PA2217
- 87 Sluijs A, Röhl U, Schouten S, et al. Arctic late Paleocene-early Eocene paleoenvironments with special emphasis on the Paleocene-Eocene Thermal Maximum (Lomonosov Ridge, Integrated Ocean Drilling Program Expedition 302). *Paleoceanography*, 2008, 23: PA1S11
- 88 Komar N, Zeebe R E. Redox-controlled carbon and phosphorus burial: A mechanism for enhanced organic carbon sequestration during the PETM. [Earth Planet Sci Lett](#), 2017, 479: 71–82

Summary for “古新世-始新世极热事件碳循环研究进展”

Carbon-cycle dynamics during the Paleocene-Eocene Thermal Maximum

Zuoling Chen^{1,2}¹ Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China;² Center for Excellence in Life and Paleoenvironment, Chinese Academy of Sciences, Beijing 100044, ChinaE-mail: chenzl@mail.iggcas.ac.cn

The Paleocene-Eocene Thermal Maximum (PETM), about 56 million years ago, was an interval of rapid, extreme global warming associated with a huge input of reduced carbon into the ocean, atmosphere and biosphere. The magnitude of carbon release during the PETM was very similar to the present anthropogenic carbon dioxide emission by burning fossil fuels. Current data estimate that the total amount of carbon released during the PETM was similar in magnitude to the IPCC RCP8.5 emission scenario. Therefore, a comprehensive study of the PETM provides a unique opportunity for understanding the relationship between carbon emission and climate change, and may help to quantitatively assess the carbon sequestration potential and rate of changes in the ecosystem, ocean and lithosphere. So far, the basic outline of massive carbon release and extreme warmth during the PETM is well established, but many important aspects regarding the carbon cycle during the event remain unresolved. The source of the carbon is still debated, with hypothesized carbon sources including methane hydrates in the ocean floor, soil organic carbon in circum-Arctic and Antarctic terrestrial permafrost, shallow-buried peat and coal, volcanic degassing, thermogenic methane caused by volcanic intrusions, and a cometary impact. The controversy can be encapsulated by two questions: (1) Is the PETM unique or only one case among many similar events? (2) What was the coupled relationship between the fine structure of the carbon isotope excursion and environmental change during the PETM? Uncertainty about the source also creates uncertainty about the amount and rate of carbon released, and the fate of the massive excess carbon at the end of the event is also poorly constrained. Here, we summarize and analyze carbon-cycle dynamics during the PETM and draw three preliminary conclusions. First, a massive release of ^{12}C -enriched carbon operated as a positive feedback to the temperature increase during the PETM, implying that methane hydrates and/or permafrost were plausible carbon sources. In particular, peak temperatures of short duration are associated with minimum carbon isotope values, suggesting that the carbon source was probably exhausted, and the positive feedback ceased. Second, the total amount of carbon released during the PETM was in the range of 4000–10000 Gt C, reflecting considerable uncertainty caused by the large range of the magnitude of the carbon isotope excursion. The average rate of carbon emission during the PETM is estimated to have been in the range of 0.15–1 Gt C/a, an order of magnitude lower than the present rate of anthropogenic carbon emission, implying that current human activities may trigger a positive feedback of the Earth's surface system and intensify global warming. Therefore, to avoid the initiation of the potential feedback of the warming-induced decomposition of reduced carbon reservoirs, as well as the accompanying major environmental perturbation, it is urgently necessary to reduce or slow the carbon emissions. Third, excess ^{12}C -enriched carbon was removed from the exogenic carbon pool during the PETM recovery on a timescale of ~40 ka, much faster than the ~100 ka that is expected for carbon uptake only by silicate weathering. These observations suggest that the fertilization effect of CO_2 on plant growth, the regeneration of carbon stores in the high-latitude terrestrial biosphere, and the enhanced efficiency of the marine “biological pump” accelerated the rate of carbon sequestration and the subsequent recovery from the PETM.

early Eocene, hyperthermal, carbon cycle, Paleocene-Eocene Thermal Maximum (PETM)doi: [10.1360/TB-2021-0652](https://doi.org/10.1360/TB-2021-0652)