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二叠纪-三叠纪之交火山活动 及其环境效应和生物响应

吴玉样*, 宋海军*, 楚道亮, 宋虎跃, 田力

中国地质大学(武汉)地质微生物与环境全国重点实验室, 地球科学学院, 湖北武汉 430074

摘要: 当今人类面临着大规模人为碳排放所导致的全球变暖, 以及由此引发的一系列全球气候变化和生态危机。地质历史时期曾发生过多次大规模火山活动所导致的极热事件, 并伴随着生物大灭绝, 这为当前全球变暖问题提供了历史借鉴。约 2.52 亿年前的二叠纪-三叠纪之交, 发生了显生宙以来最大规模的生物灭绝事件, 这一事件被广泛认为与大规模火山活动及其引发的环境变化密切相关。本文重点围绕近年来有关二叠纪-三叠纪之交火山活动的研究进展, 总结了岩浆脱气组分及其排放规模, 包括二氧化碳、甲烷、二氧化硫、卤素和重金属, 归纳了岩浆脱气直接引发的全球变暖、海洋酸化、火山冬天、酸雨、臭氧层破坏和重金属毒化等环境效应, 评估了这些环境变化对海洋和陆地生物灭绝的具体贡献, 这些讨论可加深对火山活动和生物灭绝关系的综合理解。此外, 本文将二叠纪-三叠纪之交的碳排放与现代工业碳排放进行了对比, 发现现代碳排放速率和升温速率可能处于过去 2.52 亿年以来的最高值。

关键词: 岩浆脱气; 大火成岩省; 极热事件; 碳排放; 大灭绝; 气候变化。

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Environmental Impacts and Biotic Responses to Volcanism during the Permian-Triassic Transition

Wu Yuyang*, Song Haijun*, Chu Daoliang, Song Huyue, Tian Li

State Key Laboratory of Geomicrobiology and Environmental Changes, School of Earth Sciences, China University of Geosciences (Wuhan), Wuhan 430074, China

Abstract: Humanity is facing global warming driven by large-scale anthropogenic carbon emissions, alongside a series of global climate changes and ecological crises. Throughout geological history, several hyperthermal events triggered by massive volcanic activity have occurred, often accompanied by mass extinctions. These geological events provide important analogs for modern global warming. The Permian-Triassic mass extinction (~252 Ma), the largest mass extinction event of the Phanerozoic, is widely attributed to massive volcanisms and the resulting environmental changes. This review examines recent research on volcanism during the Permian-Triassic mass extinction and summarizes the types and magnitudes of volcanic degassing, including CO₂, SO₂, halogens, and metals. We also summarize the environmental impacts of global warming, ocean acidification, volcanic winter, acid rain, ozone depletion, and metal poisoning directly triggered by

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作者简介: 吴玉样 (1992—), 男, 博士后, 博士, 主要研究方向为三叠纪古环境和古气候数值模拟。

* **通讯作者:** 吴玉样, ORCID: 0000-0001-8592-0305. E-mail: wuyuyang@cug.edu.cn; 宋海军, ORCID: 0000-0002-2721-3626. E-mail: haijun-song@cug.edu.cn

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volcanic degassing, and assess how these changes drove mass extinctions in both marine and terrestrial ecosystems. This review aims to provide a comprehensive understanding of the relationship between volcanism and mass extinction. A comparison of Permian-Triassic carbon emissions with modern anthropogenic carbon emissions reveals that modern carbon emission and warming rates may be unprecedented in the past 252 million years.

Key words: magmatic degassing; large igneous province; hyperthermal event; carbon emissions; mass extinction; climate change.

0 引言

二叠纪-三叠纪之交发生了显生宙以来最大规模的生物灭绝事件,导致超过80%的海洋生物和70%的陆生脊椎动物灭绝(Benton, 2003; Song *et al.*, 2013; 戎嘉余和黄冰, 2014; 沈树忠和张华, 2017; Fan *et al.*, 2020).直到约500万年后的中三叠世,生物多样性水平才恢复到接近灭绝前的水平(Chen and Benton, 2012; Song *et al.*, 2020).这一灭绝事件被普遍认为与大规模的火山活动密切相关,包括西伯利亚大火成岩省的火山活动(Svensen *et al.*, 2009; Burgess and Bowring, 2015; Burgess *et al.*, 2017)以及环特提斯洋和泛大陆周缘的大陆岩浆弧火山活动(殷鸿福等, 1989; 殷鸿福和宋海军, 2013; Zhang *et al.*, 2021; Chapman *et al.*, 2022).这些火山活动释放了大量的二氧化碳(CO₂)、甲烷(CH₄)、二氧化硫(SO₂)、卤素及重金属等物质,直接导致全球变暖、海洋酸化、火山冬天、酸雨、臭氧层破坏以及重金属毒化等环境效应,给海洋和陆地生物带来极大生存压力(童金南和殷鸿福, 2009; Sun *et al.*, 2012; Black *et al.*, 2014; Grasby *et al.*, 2017; Benca *et al.*, 2018; 胡修棉等, 2020; Jurikova *et al.*, 2020; Wu *et al.*, 2021; 沈树忠等, 2024; 张华等, 2024).

近年来,借助高精度放射性同位素定年技术和高分辨率的环境指标数据,人们对二叠纪-三叠纪之交火山活动的细节及其对环境和生物影响的理解有了显著提升(如Burgess *et al.*, 2017; Zhang *et al.*, 2021; Dal Corso *et al.*, 2022).本文旨在综合当前研究成果,总结火山排放物质的种类、排放量及其对大气和海洋环境的直接影响,并评估相关环境变化对生物灭绝的贡献.探讨二叠纪-三叠纪之交火山活动的环境效应与生物灭绝的关系,提供对火山活动引发的环境效应和生物大灭绝事件之间相互关系的综合理解.最后,本文将二叠纪-三叠纪之交火山碳排放与现代工

业碳排放对比,为未来应对全球变化提供历史借鉴.

1 二叠纪-三叠纪之交火山活动类型

二叠纪-三叠纪之交记录了显生宙以来最大规模的大陆溢流玄武岩,即西伯利亚大火成岩省(Wignall, 2001; Bond and Grasby, 2017; Ernst and Youbi, 2017; Clapham and Renne, 2019)和环特提斯洋及泛大陆周边的酸性大陆岩浆弧火山活动(殷鸿福等, 1989; Zhang *et al.*, 2021; Chapman *et al.*, 2022).二者可能都是二叠纪-三叠纪之交生物灭绝的重要驱动力,下面具体介绍这两种火山活动的基础信息.

1.1 西伯利亚大火成岩省

西伯利亚大火成岩省位于现今俄罗斯西伯利亚地区(图1),岩石类型从超基性到长英质,包括喷出岩、侵入岩和火山碎屑岩,但主要为低钛玄武岩及其侵入体(Ivanov *et al.*, 2013).该大火成岩省规模巨大,覆盖面积约 7×10^6 km²,体积约 4×10^6 km³,是规模最大的大陆型大火成岩省(Ivanov *et al.*, 2013).随着测年技术的进步,关于西伯利亚大火成岩省及生物灭绝层位的Ar-Ar和U-Pb测年工作不断推进(Renne and Basu, 1991; Bowring *et al.*, 1998; Shen *et al.*, 2011; Burgess *et al.*, 2014; Burgess and Bowring, 2015; Wu *et al.*, 2024a).两者的绝对年龄一致性是支持西伯利亚大火成岩省作为生物灭绝驱动力的重要依据.前人通过CA-TIMS的U-Pb测年方法,分别对金钉子煤山剖面生物灭绝层位的火山灰和西伯利亚火山岩样品进行分析,获得了高精度绝对年龄数据(Burgess *et al.*, 2014; Burgess and Bowring, 2015),并据此将西伯利亚火山作用划分为3个阶段:(1)阶段1始于(252.24 ± 0.1) Ma,以初期的火山碎屑喷出作用为特征,随后伴随熔岩喷发,约占西伯利亚火山作用总量的三分之二;(2)阶段2始于(251.907 ± 0.067) Ma,喷出作

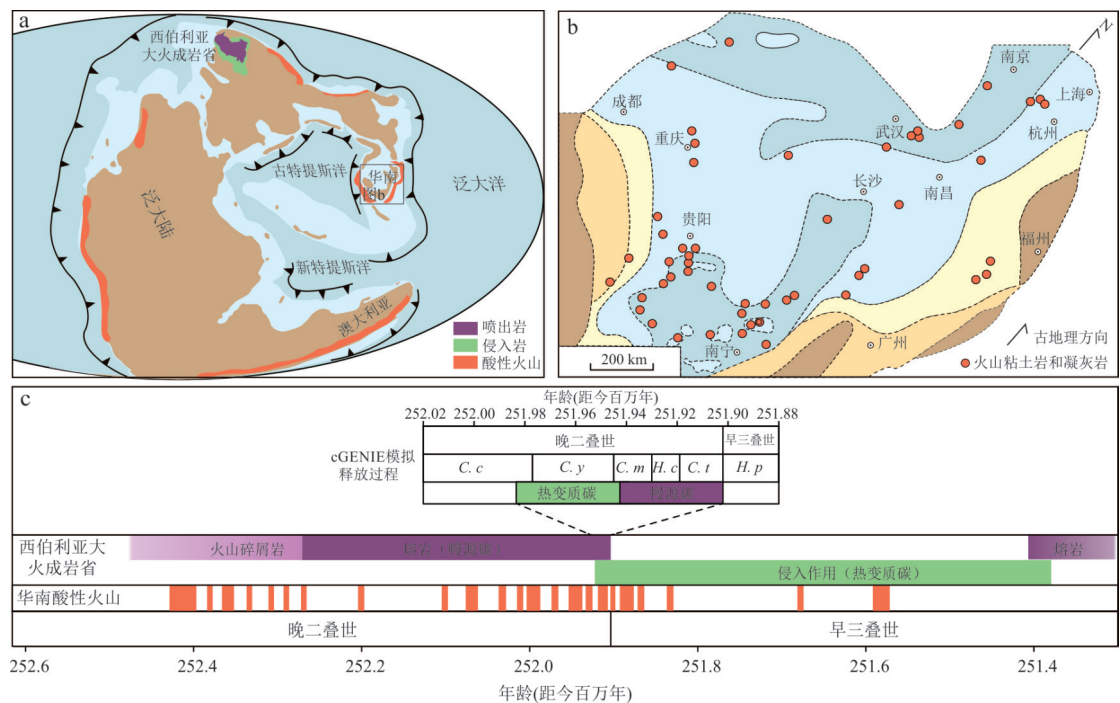


图 1 二叠纪-三叠纪之交火山活动的空间分布和时间模式

Fig.1 The spatial distribution and temporal patterns of volcanic activity at the Permian-Triassic transition

a. 二叠纪-三叠纪之交西伯利亚大火成岩省和酸性火山活动空间分布,据 Svensen *et al.* (2009、Vajda *et al.* (2020)、Chapman *et al.* (2022),古地理图修改自 Scotese (2021);b. 华南火山灰分布,修改自 Xie *et al.* (2010);c. 数值模拟的二叠纪末两阶段火山碳排放模式,据 Wu *et al.* (2023);牙形石带据 Yin *et al.* (2014),全称见图 2;西伯利亚大火成岩省和华南酸性火山的时间分布据 Burgess and Bowring (2015)、Wu *et al.* (2024a)

用暂停,伴随大规模岩床侵入体的形成;(3)阶段 3 始于 (251.483 ± 0.088) Ma,熔岩喷出再次出现,期间继续发生喷出性和侵入性岩浆活动,至少持续至 (250.2 ± 0.3) Ma. 阶段 1 火山喷出作用的起始时间比金钉子煤山剖面的二叠纪末第一幕灭绝层位年龄 $((251.941 \pm 0.037)$ Ma) 早近 30 万年,而两幕式生物灭绝时间 $((251.941 \pm 0.037)$ Ma 和 (251.880 ± 0.031) Ma) 主要对应阶段 2 的侵入作用 (Burgess *et al.*, 2017). 因此, Burgess *et al.* (2017) 提出西伯利亚岩浆侵入作用使西伯利亚地区内富含挥发分的沉积物发生热变质,释放大量温室气体,从而驱动了灭绝事件. 西伯利亚地区的沉积地层包含碳酸盐岩、蒸发岩、石油、天然气和煤层等富含挥发分沉积物 (Svensen *et al.*, 2018). 尤其是厚达百米的石炭系至二叠系的煤层,其热变质与燃烧将产生大量的 CO_2 和 CH_4 (Retallack and Jahren, 2008; Svensen *et al.*, 2009). 野外岩石样品保留了岩浆侵入作用燃烧富有机物岩层的证据 (Elkins-Tanton *et al.*, 2020). 然而,近年来也有学者对西伯利亚大火成岩省与

生物灭绝的直接关系提出质疑 (Davydov, 2021). Davydov (2021) 总结了西伯利亚地区煤层的空间和时间分布,认为侵入作用引起的热变质煤层释放 CO_2 的量较少,且释放时间主要发生在灭绝事件之后,因此不足以推动二叠纪-三叠纪之交的生物大灭绝. 尤其是对于西伯利亚地区的植物群,侵入作用似乎并未导致其灭绝,植物多样性在早三叠世印度期反而有所增加 (Davydov and Karasev, 2021).

1.2 大陆岩浆弧火山

除了西伯利亚大火成岩省,环特提斯洋及泛大陆周边的大陆岩浆弧火山与生物大灭绝之间的关系也日益受到关注 (图 1). 早在 20 世纪 80 年代,殷鸿福等 (1989) 根据广泛分布于华南地区的二叠系-三叠系界线火山灰,前瞻性地提出华南地区可能存在大规模的酸性火山活动,这些火山可能是二叠纪-三叠纪之交生物大灭绝的关键驱动力之一. 金钉子煤山剖面二叠系-三叠系界线附近的第 25 层和 28 层分别为两层火山灰 (杨遵仪等, 1991; Yin *et al.*, 2001) (图 2), 对应于两幕式灭绝层位 (Yin *et al.*, 2007; Song *et al.*, 2013), 这些火山灰广

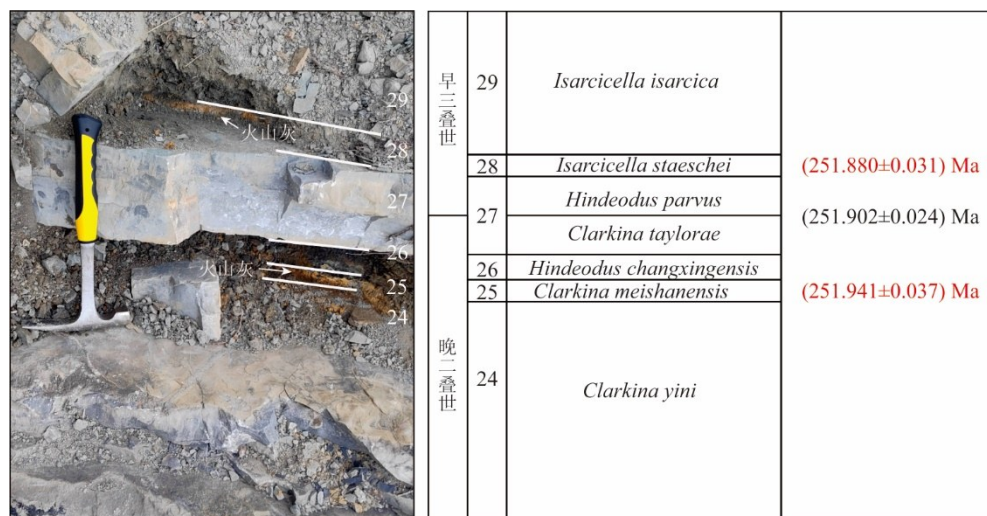


图2 浙江长兴煤山剖面二叠系-三叠系界线地层序列

Fig.2 Permian-Triassic boundary stratigraphy sequence at the Meishan section, Changxing, Zhejiang province
牙形石生物地层据 Yin *et al.* (2014); U-Pb 测年数据据 Burgess *et al.* (2014)

泛分布于华南各地(图1; Yin *et al.*, 1992; Xie *et al.*, 2010). 华南界线火山灰的厚度和数量向西南方向增加, 锆石的碳同位素和微量元素等指标进一步证实, 华南地区的火山灰成分为酸性长英质, 很可能来自华南海域西南缘的大陆岩浆弧, 与西伯利亚的基性玄武岩有显著区别(He *et al.*, 2014; 王曼等, 2018; Jiao *et al.*, 2023). Zhang *et al.* (2021) 在华南地区二叠系-三叠系界线的陆相地层中观察到大量的硫化铜矿物和 Cu 含量富集现象, 并与铜同位素的负偏和汞(Hg)浓度激增相耦合, 表明来自古特提斯洋周缘的酸性火山活动释放了大量富硫蒸气和重金属.

大陆岩浆弧火山不仅在古特提斯洋华南地区有记录, 还广泛发育在环特提斯洋及泛大陆周边, 包括澳大利亚东部、冈瓦纳西南缘、华北以及泛大陆西北缘(Yin *et al.*, 1992; Nelson and Cottle, 2019; Vajda *et al.*, 2020; Chapman *et al.*, 2022). 例如在澳大利亚东部, 锆石 U-Pb 测年揭示了该地区晚二叠世喷发了 39 000~150 000 km³ 的长英质岩浆(Chapman *et al.*, 2022). 环特提斯洋及泛大陆周边多条火山弧在 252~260 Ma 之间同步喷发, 因此被认为是二叠纪-三叠纪之交温室效应危机和生态系统压力的重要诱因(Chapman *et al.*, 2022).

2 岩浆脱气及其产物

岩浆脱气包括喷出和侵入两个过程, 喷出作用直接向地表喷出大量气体, 而侵入作用主要通过热

变质围岩途径向地表释放气体. 二者都向大气排放大量碳, 但是碳源在碳同位素组成上存在显著差异, 定量计算碳源的碳同位素组成不仅有助于推测脱气过程, 还为计算碳释放速率和总量提供了基础. 除了碳物质, 岩浆脱气还会向大气排放大量的 SO₂、卤素(如 Cl、F、Br)和重金属元素(如 Hg、Cu). 定量计算这些物质的排放规模 and 变化过程是评估火山作用对环境及生物灭绝影响的重要环节. 下面将详细介绍碳源类型以及每种脱气产物的排放规模.

2.1 碳排放过程的数值模拟

火山喷出作用直接释放幔源 CO₂ ($\delta^{13}\text{C} = -6\text{‰}$) (Sobolev *et al.*, 2011; Gales *et al.*, 2020), 而富有机质岩层(如煤层)在受到侵入作用时会释放热变质成因的 CO₂ 和 CH₄ ($\delta^{13}\text{C} = -25\text{‰}$ 至 -40‰) (Payne and Kump, 2007; Svensen *et al.*, 2009). 目前主要有 3 类数值模型可以直接或间接计算碳源的碳同位素组成, 从而评估大规模碳排放来源于侵入作用还是喷出作用. 这些模型的复杂程度从低到高依次为: 简单的碳同位素质量平衡公式(Payne *et al.*, 2010; Schneebeli-Hermann *et al.*, 2013; Wu *et al.*, 2021)、不同类型的箱式模型(Berner, 2002; Grard *et al.*, 2005; Payne and Kump, 2007)以及中等复杂程度的地球系统模型(Cui *et al.*, 2013; Cui *et al.*, 2021; Wu *et al.*, 2023). 碳同位素质量平衡公式不考虑碳循环过程, 将碳释放简化为瞬时过程(Payne *et al.*, 2010); 箱式模型的正演方法和 cGENIE(Carbon-centric Grid Enabled Integrated Earth system

表 1 二叠纪-三叠纪之交的碳排放数值模拟结果总结

Table 1 Summary of modeling results of carbon emissions at the Permian-Triassic transition

文献	模型	碳源	碳排放总量和速率
Payne <i>et al.</i> , 2010	质量平衡公式	幔源 CO ₂ (−6‰)	13 200~43 000 Gt C
Schneebeli-Hermann <i>et al.</i> , 2013		有机质(−25‰)	15 000~20 000 Gt C
Wu <i>et al.</i> , 2021		有机质(−25‰)	3 900 Gt C
		热变质成因 CH ₄ (−40‰)	6 000 Gt C
		生物成因 CH ₄ (−60‰)	12 000 Gt C
Berner, 2002	箱式模型	生物成因 CH ₄ (−65‰),幔源 CO ₂ (−6‰)和生 产力下降	2 000 Gt CH ₄
Grard <i>et al.</i> , 2005	箱式模型和能量平衡模型	幔源 CO ₂ (−5‰)和生产力下降	/
Komar and Zeebe, 2016	箱式模型 (LOSCAR)	幔源 CO ₂ (−5‰) 和生产力下降	12 000 Gt C
Payne and Kump, 2007	箱式模型	热变质成因碳(−25‰)	12 000 Gt C
Clarkson <i>et al.</i> , 2015	箱式模型	阶段 1: 甲烷(−50‰) 或有机质(−25‰)或 混合(−12.5‰)	阶段 1: 3 840~15 600 Gt C
		阶段 2: 幔源 CO ₂ 和碳酸盐岩(0‰)	阶段 2: 24 000 Gt C
		阶段 1: 幔源 CO ₂ (−6‰)	9 600 Gt C
Jurikova <i>et al.</i> , 2020	箱式模型	阶段 2: 热变质成因碳(−18‰)	96 000 Gt C
Dal Corso <i>et al.</i> , 2020	C-Hg 耦合箱式模型	幔源 CO ₂ (−5‰) 和陆相有机质氧化 (−25‰)	/
Cui <i>et al.</i> , 2013	cGENIE 模型	有机质(−25‰)	22 400 Gt C
		热变质成因 CH ₄ (−40‰)	11 500 Gt C
		生物成因 CH ₄ (−60‰)	7 000 Gt C
Cui <i>et al.</i> , 2021		幔源 CO ₂ 和热变质成因碳(−15‰)	36 200 Gt C; 5 Gt C/a
Wu <i>et al.</i> , 2023		阶段 1: 幔源 CO ₂ (−9‰)	5 000 Gt C; 0.2 Gt C/a
		阶段 2: 热变质成因 CO ₂ 和 CH ₄ (−16‰)	21 000 Gt C; 0.7 Gt C/a

model)地球系统模型的单参数反演方法均需要对碳源类型进行人为假设.这些方法的局限性和采用的碳同位素负偏程度的差异导致了火山碳源类型一直存在较大争议(表 1).例如 Jurikova *et al.* (2020)利用生物地球化学的箱式模型,结合腕足类化石硼同位素记录的 pH 值,正演推测先释放富集 ¹³C 的幔源 CO₂ (-6‰),随后在大灭绝关键层位释放碳同位素组成较低的碳物质 (-18‰),揭示生物灭绝与热变质成因碳密切相关.另一方面,Clarkson *et al.* (2015)得出了相反的结论,先释放碳同位素组成较低的碳 (<-12.5‰),随后释放碳同位素组成接近 0‰ 的碳源.通过海相藻类来源的单体碳同位素结合 cGENIE 的单参数反演方法,Cui *et al.* (2021)评估了二叠纪末的碳排放过程,碳排放总量约为 36 000 Gt C (Gt=10¹⁵g),速率高达~5 Gt C/a.在温度和 pH 指标数据的约束下,Cui *et al.* (2021)认为碳来源是混合的 (~-15‰),但是以幔源 CO₂ 为主.

相较于箱式模型的正演和 cGENIE 的单参数反演方法,cGENIE 模型的“双参数反演”无需假设轻

碳来源,能够直接计算碳源的连续演变过程(Wu *et al.*, 2023).模拟结果揭示了二叠纪末生物灭绝期间碳排放的两阶段特征:碳排放一期(251.994~251.942 Ma)以岩浆侵入富有机质岩层为主,缓慢释放碳同位素值偏低的热变质成因 CO₂ 和甲烷 (-25‰~-40‰),速率为 0.05~0.20 Gt C/a,持续了近 50 ka;碳排放二期(251.942~251.902 Ma)火山喷出作用加强,快速排放大量幔源 CO₂ (-6‰),峰值可达到 0.7 Gt C/a.此期间碳排放总量的最佳估计为 26 000 Gt C (范围为 15 500~55 700 Gt C).数值模拟的碳排放过程聚焦于二叠纪末碳同位素快速下降的关键时段,也是西伯利亚大火成岩省阶段 1 和阶段 2 的交界处(图 1).该交界处存在两个先后的 U-Pb 测年数据,侵入岩为(251.907±0.067) Ma、喷出岩为(251.901±0.061) Ma (Burgess and Bowring, 2015),可能反映了西伯利亚岩浆在这期间存在侵入作用向喷出作用转变的过程.这进一步支持了先释放热变质碳后排放大规模幔源 CO₂ 的模拟结果.地球系统模型 cGENIE 的双参数反演实验揭示了这段时间内火山排气

的两阶段模式,并建立了与二叠纪末碳同位素负偏、全球变暖、海洋酸化等环境事件与二叠纪末第一幕生物灭绝之间的关系(Wu *et al.*, 2023).

2.2 二氧化碳浓度

总体而言,这些模拟结果表明,幔源CO₂和热变质成因碳的混合很可能是二叠纪末大规模碳释放的主要来源,在0.1~1.0 Ma内10⁴~10⁵ Gt数量级的碳被释放到大气(表1).如此大规模碳排放将导致大气中温室气体CO₂浓度(*p*CO₂)激增.那么,二叠纪-三叠纪之交*p*CO₂究竟升高了多少?早期研究主要集中于显生宙长尺度和晚二叠世的*p*CO₂变化,其时间分辨率较低(大于1 Ma)且缺少可靠的早三叠世初期数据.前人利用古土壤次生碳酸盐指标重建了400 Ma以来的大气CO₂浓度变化,其中在晚二叠世只有一个CO₂数据点,浓度约1 000×10⁻⁶(10⁻⁶=1 ppm),后续重新计算修订为约400×10⁻⁶(Ekart *et al.*, 1999; Foster *et al.*, 2017).南非卡鲁盆地晚二叠世的古土壤次生碳酸盐碳同位素记录了相对较高的晚二叠世*p*CO₂(883×10⁻⁶~1 325×10⁻⁶)(Gastaldo *et al.*, 2014).基于植烷有机碳同位素指标的显生宙*p*CO₂变化趋势显示,晚二叠世长兴阶的*p*CO₂达到873×10⁻⁶~1 085×10⁻⁶,早三叠世初期*p*CO₂升高至约1 600×10⁻⁶(Witkowski *et al.*, 2018).冈瓦纳

地区银杏叶气孔指数表明,晚二叠世大气CO₂水平达到300×10⁻⁶~500×10⁻⁶,到了早三叠世升高至7 832×10⁻⁶(Retallack, 2009, 2013).但是这些植物的时代归属和属种鉴定存在一定争议,影响了CO₂估计值的可靠性(Li *et al.*, 2019).而来自华南长兴期大隆组的松柏类化石分类和时代明确,利用其气孔指数重建的晚二叠世*p*CO₂范围达300×10⁻⁶~520×10⁻⁶(Li *et al.*, 2019).

近年来的几项古大气CO₂浓度研究提供了相对高分辨率的CO₂变化趋势,有效限定了二叠纪-三叠纪之交大气CO₂浓度升高幅度.Wu *et al.* (2021)利用C₃植物有机碳同位素新指标,通过提取层位连续的微米级植物化石碎屑,解决了常规*p*CO₂指标材料(如植物气孔和古土壤等)在该时期稀少的难点.通过高分辨率的植物有机碳同位素记录,定量重建了古-中生代之交*p*CO₂的高时间分辨率连续变化趋势.结果显示,大气CO₂浓度由晚二叠世晚期的420×10⁻⁶快速升高到灭绝期间的约2 500×10⁻⁶(图3),揭示了6倍*p*CO₂的升高与地质记录的海水表层温度升高趋势相耦合,这为显生宙以来最大升温事件提供了新证据(Wu *et al.*, 2021).华南上寺剖面的植烷有机同位素指标显示,*p*CO₂从晚二叠世的300×10⁻⁶~500×10⁻⁶上升到早三叠世早期的峰值2 600×10⁻⁶,与植物有机碳同位素的估计值相似

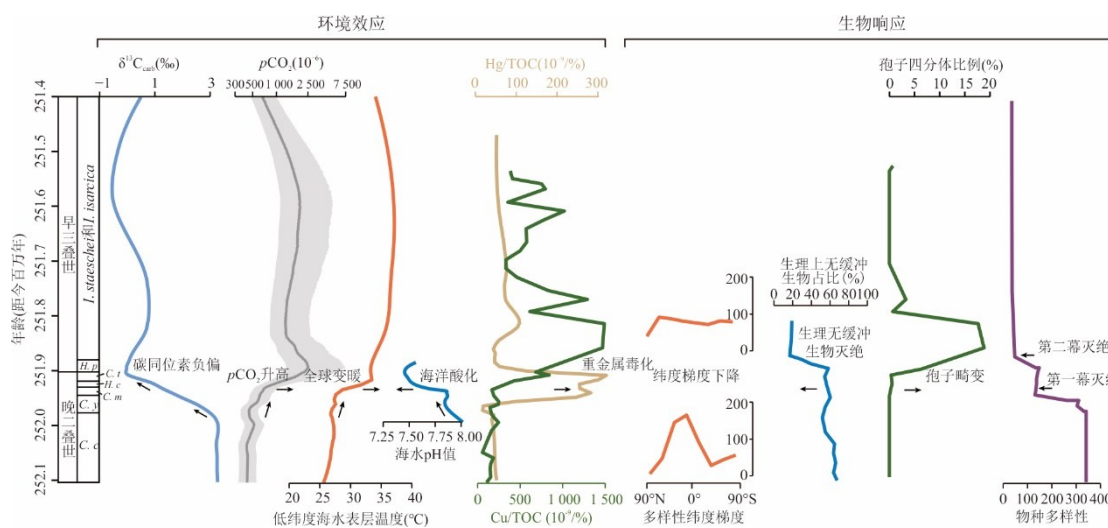


图3 二叠纪-三叠纪之交火山活动的环境效应和生物响应的综合指标数据

Fig. 3 Comprehensive proxy data on the environmental effects and biological responses to volcanic activity at the Permian-Triassic boundary.

数据来源:全球海相碳酸盐岩碳同位素,利用C₃植物有机碳同位素重建的大气CO₂浓度,以及低纬度地区牙形石氧同位素数据计算的海水表层温度,据Wu *et al.* (2021);利用腕足硼同位素计算的海水pH值,据Jurikova *et al.* (2020);海相综合Hg/TOC数据,据Dal Corso *et al.* (2022);黔西滇东地区陆相地层Cu/TOC和石松类孢子的四分体比例,据Chu *et al.* (2021);物种多样性纬度梯度,据Song *et al.* (2020);生理上无缓冲生物的占比和物种多样性记录的两幕式灭绝,据Song *et al.* (2013)

(Shen *et al.*, 2022). 然而, 植烷数据还记录了二叠纪末生物灭绝层位的 $p\text{CO}_2$ 下降, 最低至 270×10^{-6} , 与该层位的高温指标记录相矛盾, 有待未来进一步验证. 基于古土壤钙结壳的碳同位素重建的早三叠世以来 $p\text{CO}_2$ 变化趋势显示, $p\text{CO}_2$ 从晚二叠世的 $412 \times 10^{-6} \sim 919 \times 10^{-6}$ 上升至早三叠世早期的 $2181 \times 10^{-6} \sim 2610 \times 10^{-6}$ (Joachimski *et al.*, 2022). 总体来看, 这几项不同指标均记录了相似的 CO_2 升高峰值, 峰值达到 $2500 \times 10^{-6} \sim 2600 \times 10^{-6}$. 这不仅为理解显生宙最大升温事件的驱动机制提供了直接证据, 同时对定量研究地质历史时期升温背景下的地球气候敏感性有着重要科学价值.

2.3 二氧化硫和卤素

二氧化硫和卤素(如 Cl、F、Br)也是岩浆脱气过程中释放到大气中的关键挥发性成分(Svensen *et al.*, 2009). 基于西伯利亚地幔玄武岩包裹体中硫、氯和氟的含量, 估算的侵入和喷出作用的总脱气量约为 $6300 \sim 7800 \text{ Gt S}$, $3400 \sim 8700 \text{ Gt Cl}$ 和 $7100 \sim 13600 \text{ Gt F}$ (Black *et al.*, 2012). 另一项研究显示西伯利亚岩石圈富含大量卤素, 其中约 70% 被地幔柱吸收后于侵入过程中释放到大气中. 基于西伯利亚大火成岩省的熔体包裹体估算的 Cl 释放总量约为 8700 Gt , 同时释放了相应的 Br 和 I (Broadley *et al.*, 2018). 如果西伯利亚大火成岩省以喷出作用为主, 而非热变质成因, 估算的 HCl 释放总量接近 18000 Gt (Sobolev *et al.*, 2011). 除西伯利亚大火成岩省外, 华南地区二叠系-三叠系界线陆相地层中发现的大量硫化铜矿物表明, 华南周缘的酸性火山也释放 SO_2 , 其释放规模估算为 $2.4 \sim 47.1 \text{ Gt S}$, 相当于现代每年 SO_2 释放量的 $10 \sim 200$ 倍 (Zhang *et al.*, 2021).

2.4 重金属元素

火山活动脱气过程不仅释放挥发性物质, 还释放金属物质, 如 Hg、Cu、Ni、Pb 和 Zn 等, 这些金属在沉积物中形成富集层位. 二叠纪-三叠纪之交的沉积物中 Hg (或 Hg/TOC) 显著增加, 这一现象在全球海相和陆相地层中广泛存在, 包括古特提斯洋 (Wang *et al.*, 2018; Shen *et al.*, 2019a, 2021)、新特提斯洋 (Sial *et al.*, 2020; Chen *et al.*, 2024)、泛大洋 (Shen *et al.*, 2019a) 和泛大陆北部海域 (Grasby *et al.*, 2017), 以及陆相盆地华南黔西滇东 (Shen *et al.*, 2019b; Chu *et al.*, 2020)、华北地区 (Chu *et al.*, 2025)、新疆准噶尔盆地 (Dal Corso *et al.*,

2024)、悉尼盆地以及卡鲁盆地 (Shen *et al.*, 2023). 不同水深和陆相盆地中汞含量峰值层位的差异可能由多种因素共同造成, 包括沉积环境的差异、汞吸附载体差异以及地层对比的不确定性 (Shen *et al.*, 2019a; Chu *et al.*, 2020; Chen *et al.*, 2024). 尽管如此, 全球范围内的海相汞数据汇总表明, 汞富集层位基本与二叠纪末的第一幕灭绝事件相耦合 (图 3) (Dal Corso *et al.*, 2022). 与背景时期的 Hg/TOC 低值 ($< 50 \times 10^{-9} \%$, TOC 为质量百分含量) 相比, 富集层位的 Hg/TOC 峰值可超过 $300 \times 10^{-9} \%$. 除了 Hg 富集, 二叠系-三叠系界线地层还记录了 Cu (Chu *et al.*, 2021; Zhang *et al.*, 2021)、Zn (Jiao *et al.*, 2023)、Ni (Rampino *et al.*, 2017) 以及 Pb (Grasby *et al.*, 2015) 等金属元素的大量富集. $\Delta^{199}\text{Hg}$ 的正向偏移表明, 这些 Hg 和其他金属元素来自火山, 通常认为来源于西伯利亚大火成岩省的释放, 释放速率是每年 $0.8 \sim 10.0 \text{ Gg}$, 累计释放量达到 0.4 Gt (Grasby *et al.*, 2015), 并通过大气远距离输送至全球范围 (Grasby *et al.*, 2017). 华南黔西滇东地区的硫化铜沉积物表明, 华南周缘火山活动同样释放了大量重金属. 据估算约 1 m 厚的硫化铜沉积层反映出华南酸性火山释放的铜量超过 1.9 Gt . 另一方面, 陆地生态系统崩溃后, 大量陆地有机质和土壤的氧化可能进一步向环境中释放大量 Hg 和 Cu, 二叠纪-三叠纪之交富集的重金属很可能具有多源性 (Chu *et al.*, 2020; Dal Corso *et al.*, 2020).

3 火山活动的环境效应与生物响应

火山活动释放的大量 CO_2 、 CH_4 、 SO_2 、卤素及重金属引发了多种环境效应. 这些效应包括由温室气体 CO_2 浓度激增引起的长期全球升温和海洋酸化, SO_2 可能导致的短暂降温 (火山冬天), CO_2 和 SO_2 共同引发的酸雨, 卤素释放引起的潜在臭氧层破坏, 以及重金属富集的毒化作用 (图 4 和图 5). 这些环境效应对海洋和陆地生物产生了不同的影响, 并最终共同导致了二叠纪-三叠纪之交的生物大灭绝.

3.1 全球变暖

显著的 CO_2 浓度增加导致了氧同位素所记录的二叠纪-三叠纪之交极端高温. 特提斯洋低纬度地区的牙形石氧同位素记录了近 10°C 的异常升温, 包括华南地区 (Joachimski *et al.*, 2012; Sun *et al.*, 2012; Chen *et al.*, 2013, 2016)、伊朗地区 (Schobben *et al.*, 2014) 和亚美尼亚地区 (Joachimski *et al.*,

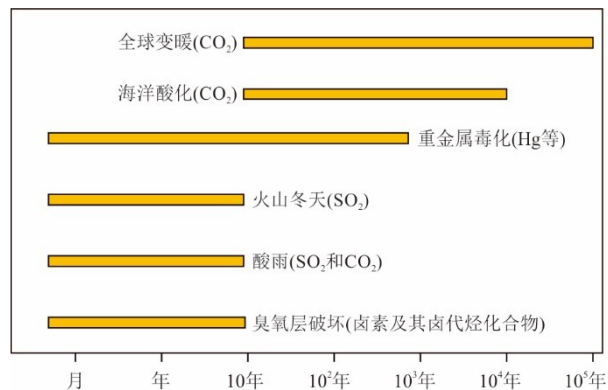


图4 火山活动环境效应的时间尺度

Fig.4 The time scale of environmental effects of volcanism 修改自 Wignall (2001), 时间尺度数据更新自数值模拟实验, 据 Hönlisch *et al.* (2012)、Black *et al.* (2014)、Black *et al.* (2018)、Grasby *et al.* (2020)

2020). 此外, 秦岭和西藏地区的腕足类和介形虫壳体氧同位素出现显著负偏, 反映了超过 10°C 的升温 (Garbelli *et al.*, 2016; Wang *et al.*, 2020; Gliwa *et al.*, 2022). 二叠纪-三叠纪之交的快速升温显著加速了古生代晚期的长期升温趋势, 最终导致了显生宙最为剧烈的一次变暖事件, 即古生代末大变暖事件 (Song and Scotese, 2023).

二叠纪-三叠纪之交的升温呈现出两阶段变化模式, 从晚二叠世牙形石 *C. changxingensis* 带顶部到 *C. yini* 带顶部 (对应 251.994~251.942 Ma), 小

幅度缓慢增温 $1\sim 2^{\circ}\text{C}$; 随后从 *C. meishanensis* 带至二叠系-三叠系界线 (对应 251.942~251.902 Ma), 大幅度升温 $7\sim 8^{\circ}\text{C}$ (图 3; Joachimski *et al.*, 2012; Sun *et al.*, 2012). 这一变化与先释放少量热变质碳, 随后大量排放慢源 CO_2 的火山碳排放模式相耦合 (Wu *et al.*, 2023). 尽管最初升温幅度较小, 数值模拟表明, 当 CO_2 浓度升至约 800×10^{-6} 时, 升温能够引起显著的厄尔尼诺效应 (Sun *et al.*, 2024). 这一效应可能导致降水的季节性增强与显著干旱 (Franks *et al.*, 2014; Benton, 2018; 宋汉宸等, 2023; Sun *et al.*, 2024), 进一步促进野火频发并引发陆地去森林化 (Chu *et al.*, 2020; Vajda *et al.*, 2020). 例如, 华南黔西滇东、新疆准噶尔盆地和悉尼盆地的陆相沉积物中记录了高丰度的炭屑, 这一现象发生在二叠纪末海相主幕灭绝之前, 反映出小幅升温已引发的热带和中纬度陆地生态系统的提前崩溃 (Chu *et al.*, 2020; Vajda *et al.*, 2020; Cai *et al.*, 2021). 更多的陆相地层高精度测年数据和化学地层证据表明, 陆相生态系统的扰动可能比二叠纪末的海相主幕灭绝提前 60~370 ka (Fielding *et al.*, 2019; Chu *et al.*, 2020; Gastaldo *et al.*, 2020; Wu *et al.*, 2020). 近年来有学者提出, 不同陆相盆地的生物危机也存在不同步 (Chu *et al.*, 2025), 甚至认为部分陆相盆地的生物灭绝反而晚于海相灭绝, 可能反映了不同纬度

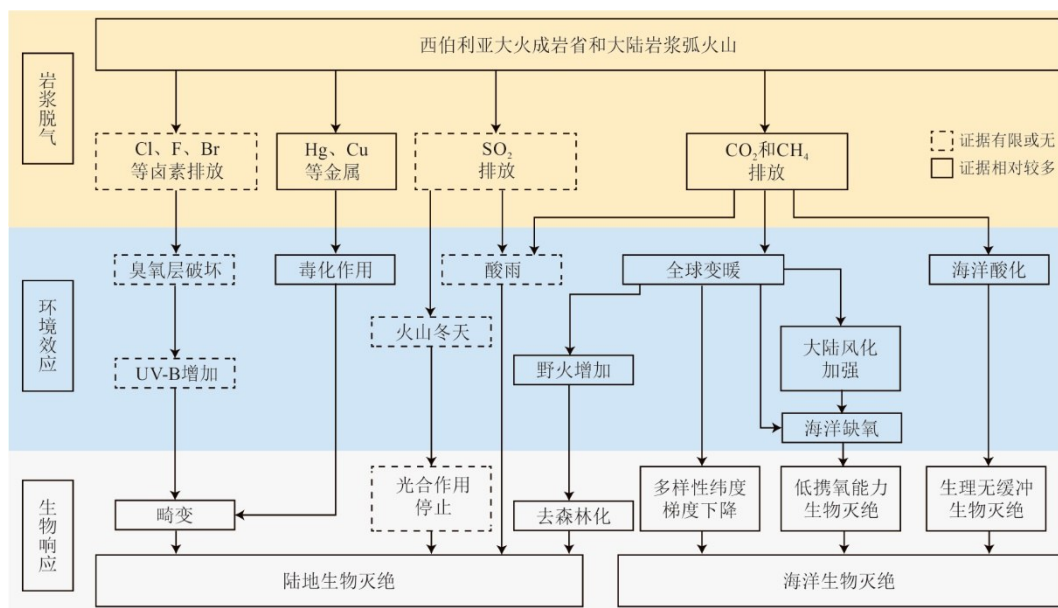


图5 二叠纪-三叠纪之交火山脱气产物、环境和生物灭绝之间的关系

Fig.5 The relationship between volcanic degassing, the environment, and mass extinction at the Permian-Triassic boundary

修改自 Grasby and Bond (2023)

地区对升温响应的差异性(Wu *et al.*, 2024a).

致命高温引发了不同纬度的海洋动物的选择性灭绝,并促使它们向极地迁移(Penn *et al.*, 2018; Song *et al.*, 2020).然而,上述研究报道了两种相反的灭绝模式:一种认为高纬度地区的灭绝率最高(Penn *et al.*, 2018),另一种则指出热带地区的灭绝率最高(Song *et al.*, 2020).这一差异可能归因于统计方法和数据来源的不同.第一种模式仅考虑了二叠纪末的第一幕灭绝数据,忽略了早三叠世早期的第二幕灭绝数据(Penn *et al.*, 2018);第二种模式则综合分析了两幕式灭绝的数据(Song *et al.*, 2020).与此同时,升温引发的大陆风化显著加强,增加了营养盐(如磷酸盐)向海洋的输送,进而促进了海洋富营养化,最终导致缺氧和硫化(Song *et al.*, 2012; Yin *et al.*, 2012; Grasby *et al.*, 2013; Zhang *et al.*, 2018; Hülse *et al.*, 2021; Wu *et al.*, 2024b).海洋缺氧导致生物的灭绝具有选择性,携氧能力较低的类群(如有孔虫、腕足类)相比具有较高效率携氧蛋白的类群(如双壳类、腹足类、鱼类、牙形石等)经历了更高的灭绝率,并表现出更显著的小型化特征(Song *et al.*, 2024; Yang *et al.*, 2024).

3.2 海洋酸化

大气CO₂浓度升高会使更多二氧化碳溶解于海水中,导致pH值下降并引发海洋酸化(Hönisch *et al.*, 2012).二叠纪-三叠纪之交海洋酸化的早期证据包括大贵州滩微生物岩底部的溶蚀面(Payne *et al.*, 2007).然而Wignall *et al.* (2009)提出质疑,认为该溶蚀面是由海退导致的暴露面,牙形石生物地层证据则进一步支持了这一观点(Yin *et al.*, 2014).二叠纪-三叠纪之交碳酸盐岩和牙形石的 $\delta^{44}\text{Ca}$ 显示出显著负偏,这一现象被解释为海洋酸化的结果(Payne *et al.*, 2010; Silva-Tamayo *et al.*, 2018; Song *et al.*, 2021).但是钙同位素数据模型显示,海水 $\delta^{44}\text{Ca}$ 的变化不仅反映海洋酸化,还受到多种因素的共同影响,包括大陆架碳酸盐岩风化增强、碳酸盐沉积减少、矿物学变化以及海水饱和状态的改变(Komar and Zeebe, 2016).在华南地区,第一幕生物灭绝层位附近记录了大量仅在酸性条件下形成的白铁矿沉积,其含量急剧增加,且 $\delta^{34}\text{S}$ 显著下降,这可能指示海水发生了快速酸化(Li *et al.*, 2023).海相碳酸盐岩硼同位素的负偏揭示了显著的pH值下降(~ 0.7),但这一变化出现在早三叠世初期的第二幕灭绝层位(Clarkson *et al.*, 2015),晚于

二叠纪末大气CO₂浓度上升和碳同位素负偏,因而该记录是否能够作为海洋酸化的有力证据存在争议(Dal Corso *et al.*, 2022).目前,最直接且可靠的海洋酸化证据来自意大利和我国华南腕足类化石的硼同位素负偏.这些数据揭示海水pH值下降与二叠纪末碳同位素负偏相耦合,在二叠系-三叠系界线附近达到最低值,pH值的下降幅度约为0.6个单位(Jurikova *et al.*, 2020).这与中等复杂程度地球系统模型cGENIE计算的约0.7个单位的pH值下降幅度基本一致(Wu *et al.*, 2023).目前仍亟需其他地区的地球化学指标记录,以支持意大利和我国华南腕足类化石硼同位素负偏所揭示的海洋酸化.

海洋酸化引发了生物的选择性灭绝,生理上无缓冲机制的生物(如珊瑚、腕足类和有孔虫)由于代谢率较低且生成碳酸钙骨骼需耗费大量能量,因而更容易灭绝;而生理上具备缓冲机制的生物(如双壳类、腹足类、菊石和牙形石)在危机中则能够较好地存活(Clapham and Payne, 2011; Song *et al.*, 2013; 宋海军和童金南, 2016).Garbelli *et al.* (2017)对腕足外壳的生物成矿进行了深入研究,发现有机质含量较高的腕足类型能够有效保护钙质外壳免于溶解,从而更容易在二叠纪末的海洋酸化中避免灭绝.对现生软体动物的观察与实验研究表明,海水酸化会引起壳体出现畸变特征(Foster *et al.*, 2022).然而,斯瓦尔巴群岛早三叠世早期双壳化石未记录畸变特征,这至少表明海洋酸化对高纬度地区早三叠世早期斯瓦尔巴群岛的影响较小(Foster *et al.*, 2022).

3.3 火山冬天

不同于温室气体CO₂,火山排放的SO₂会迅速转化为硫酸盐气溶胶,遮挡光照并降低气温,从而引发“火山冬天”效应(Schmidt *et al.*, 2016).全耦合地球系统模型CESM的模拟结果显示,若西伯利亚火山以每年喷发2 000 Tg二氧化硫的规模持续10 a,全球平均气温将下降1.5~3.0 °C,而北半球陆地年均气温的下降幅度更为显著,可达5~15 °C(Black *et al.*, 2018).这是由于西伯利亚地幔玄武岩省位于北半球中高纬度地区,导致大部分硫酸盐气溶胶滞留在北半球(Black *et al.*, 2018).然而,几乎所有温度指标都未显示显著的降温,仅在华南蓬莱滩剖面的牙形石氧同位素数据中,在快速升温之前记录到一个可能的降温数据点(Shen *et al.*, 2019c).此外,利用植烷指标重建的CO₂浓度

在二叠纪末生物灭绝层位出现下降,最低达到 270×10^{-6} (Shen *et al.*, 2022),但这一趋势未被其他 CO_2 指标记录.火山冬天引起的光照下降在理论上会抑制植物光合作用(图5).然而,现有温度指标的时间分辨率最高约为10 ka,难以捕捉“火山冬天”现象及其对生物短期响应的影响,有待未来更高分辨率的温度指标和化石记录进行验证.

3.4 酸雨

全耦合地球系统模型CESM的模拟结果表明, CO_2 浓度增加十倍会导致全球雨水的pH值显著下降,降至约4 (Black *et al.*, 2014).火山碎屑喷发将 SO_2 注入平流层,使雨水的pH值进一步降低至2~3,北半球尤为明显 (Black *et al.*, 2014).酸雨的可能证据来自在意大利北部发现的生标化合物香草醛(这种物质是土壤有机物在酸性条件下分解的产物),其丰度表现为脉冲式增加 (Sephton *et al.*, 2015).南非卡鲁盆地地层中的硫含量及其同位素提供了酸雨的其他地球化学证据,其中硫化物的增多被解释为酸雨向淡水环境输送大量硫酸盐的结果 (Maruoka *et al.*, 2003).然而,卡鲁盆地的陆地灭绝事件发生在硫含量及其同位素变化之前,这降低了该结论的可靠性.新疆准噶尔盆地和悉尼盆地的陆相沉积物记录了显著的硫同位素负偏,这与陆相碳同位素负偏和生物灭绝层位相耦合,为火山 SO_2 释放引发的酸雨事件提供了相对可靠的证据 (Li *et al.*, 2022; Dal Corso *et al.*, 2024).目前关于酸雨的记录较少,缺乏确凿证据来揭示二叠纪-三叠纪之交酸雨的强度、分布等具体细节,同时也缺少酸雨对生物影响的化石证据.

3.5 臭氧层破坏

火山活动释放的卤素及其形成的卤代烃化合物进入平流层后,与臭氧发生化学反应,消耗臭氧并破坏臭氧层,从而增强了UV-B辐射 (Beerling *et al.*, 2007).全耦合地球系统模型CESM的模拟结果显示,西伯利亚大火成岩省喷出作用释放的HCl导致臭氧耗损达5%~30%,而热变质煤层和蒸发岩所释放的HCl使臭氧耗损进一步提升至55%~67% (Black *et al.*, 2014).由于溴的臭氧消耗效能约为氯的45倍,西伯利亚大火成岩省释放的大量溴进入平流层后,可能进一步加剧臭氧耗损,比例达20%, (Sobolev *et al.*, 2011).上述卤素脱气规模足以在二叠纪末危机期间引发全球臭氧几乎完全耗损,但由于大气臭氧在10 a内快速恢复,全球臭氧层

长期受损的可能性较低(图4) (Black *et al.*, 2014).现代实验模拟表明,在高UV-B强度下,现生松柏类花粉的畸形频率增加了5倍.尽管所有树木在增强的UV-B环境下能够存活,但均失去了生殖能力 (Benca *et al.*, 2018).二叠系-三叠系界线的海相和陆相地层中,均发现高丰度的畸形孢子和花粉 (Visscher *et al.*, 2004; Hochuli *et al.*, 2017; Chu *et al.*, 2021),这一发现支持了二叠纪-三叠纪之交臭氧层被破坏导致UV-B辐射增强的推测.藏南海相地层中的孢粉外壁记录了高水平的UV-B吸收化合物,这是植物为抵抗UV-B辐射的产物 (Liu *et al.*, 2023).这一现象与汞富集和显著碳同位素负偏的层位一致,表明臭氧层破坏与陆地生物灭绝之间存在密切联系 (Liu *et al.*, 2023).

3.6 重金属毒化作用

沉积记录中高浓度的重金属(如Hg、Cu、Ni)在被生物体大量吸收后,会引发大量活性氧的产生,从而破坏蛋白质和DNA,最终干扰生物的生理活动,甚至导致死亡 (Nagajyoti *et al.*, 2010).数值模拟结果显示,西伯利亚大火成岩省喷发向大气中释放的汞浓度比正常背景水平高出若干数量级 (Grasby *et al.*, 2020).这些汞沉积到全球环境中后,引发了一系列持续超过1 ka的金属毒化作用,最终对海洋生物和陆地动植物造成毒害(图4).金属毒化作用同样影响了热带地区灭绝后的幸存植物.华南黔西滇东地区,在大羽羊齿植物群灭绝层之上的地层中,石松孢子四分体显著增加,与汞和铜富集峰值相一致,表明幸存植物可能面临较高金属浓度的环境压力,从而导致畸变 (Chu *et al.*, 2021).然而,畸变的孢粉不仅与金属毒化作用密切相关,臭氧层破坏引起的UV-B辐射增强同样可能带来环境压力,从而引发孢粉畸变 (Benca *et al.*, 2018).因此,孢粉畸变可能是多种环境压力共同作用的结果(图5).

4 二叠纪-三叠纪之交火山与现代工业碳排放的对比

二叠纪-三叠纪之交的火山活动及其引发的环境效应与生物响应,为当前全球变化问题提供了重要的历史借鉴.特别是对深时火山碳排放过程的研究,揭示了导致全球生态系统剧变的碳排放规模和速率,这为评估现代工业碳排放的严重性提供了重要参考.在二叠纪末的碳同位素负偏启动阶段(251.994~251.902 Ma),碳排放总量估算为26 000 Gt,范围在

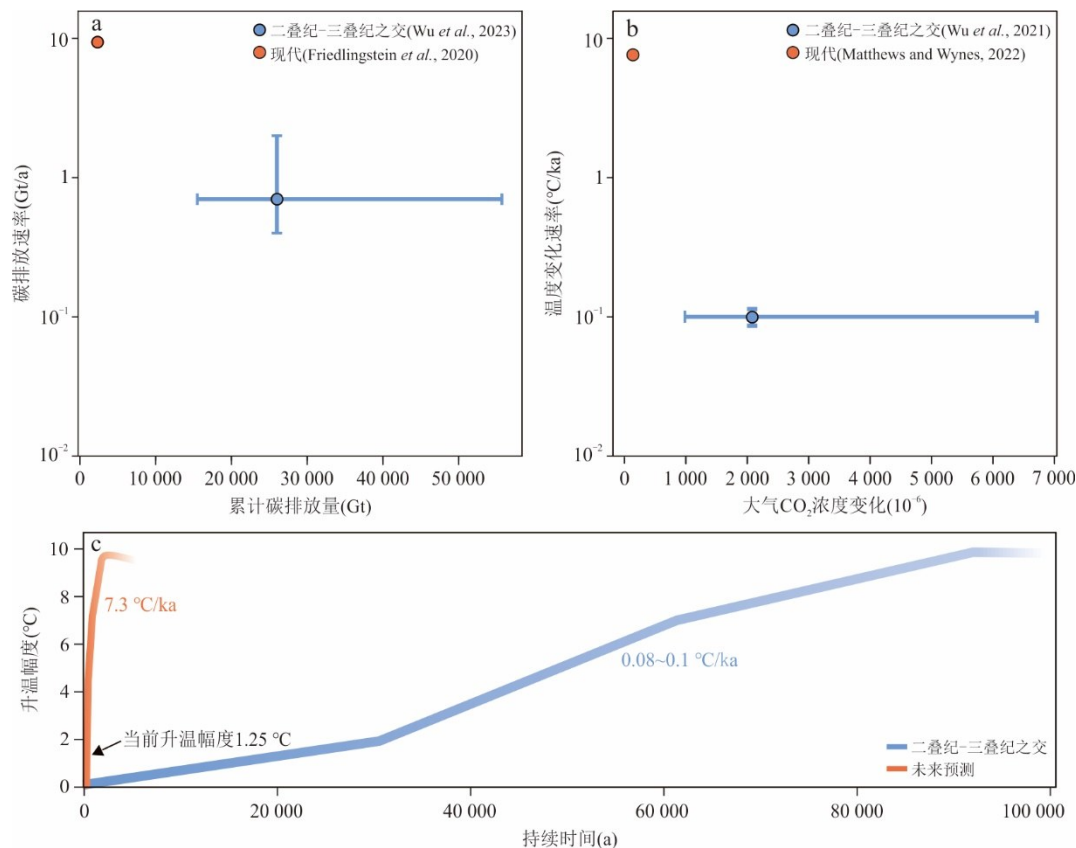


图6 现代人为和二叠纪-三叠纪之交火山的碳排放对比

Fig.6 A comparison of modern anthropogenic carbon emissions with volcanic carbon emissions during the Permian-Triassic crisis
a. 累计碳排放量和碳排放速率; b. 大气 CO_2 浓度变化和温度变化速率; c. 二叠纪-三叠纪之交和未来预测的升温趋势

15 500~55 700 Gt 之间 (Wu *et al.*, 2023). 然而, 该模拟实验没有涉及碳同位素启动阶段前后时间存在的火山作用 (Burgess *et al.*, 2017), 因此二叠纪-三叠纪之交的碳释放总量很可能高于 26 000 Gt. 例如, 地球生物化学箱式模型模拟了二叠纪-三叠纪之交前后 1 Ma 的火山碳排放过程, 计算得到 105 600 Gt 的碳排放 (Jurikova *et al.*, 2020). 尽管碳同位素负偏启动阶段只持续了近 90 ka, 但其碳排放量占 1 Ma 火山碳排放总量的 15%~53%, 这一阶段是碳快速排放的关键时期, 碳排放峰值速率高达 0.7 Gt/a, 范围在 0.4~2 Gt/a (Wu *et al.*, 2023).

尽管二叠纪-三叠纪之交发生了显生宙中规模最大的碳排放事件, 其排放速率仍比现代工业碳排放速率低一个数量级. 2010 年至 2019 年, 人类工业碳排放平均速率为 9.6 Gt/a (Friedlingstein *et al.*, 2020), 远高于二叠纪-三叠纪之交的火山碳排放速率. 从 1850 年到 2019 年, 工业碳排放累计约 2 400 Gt, 导致全球大气 CO_2 浓度从工业革命前的 $\sim 280 \times 10^{-6}$ 上升至当前的 $\sim 420 \times 10^{-6}$. 与

1850 年至 1900 年的平均温度相比, 截至 2022 年 6 月, 全球气温已上升 1.25 °C (Damon Matthews and Wynes, 2022). 尽管当前的 $p\text{CO}_2$ 浓度和温度升高幅度远低于二叠纪-三叠纪之交的变化水平 ($p\text{CO}_2$ 变化 $2\,000 \times 10^{-6}$ 以上, 温度变化 ~ 10 °C), 但升温平均速率高达 7.3 °C/ka, 比二叠纪-三叠纪之交 (0.08~0.1 °C/ka) 高出 1 至 2 个数量级 (图 6). 因此, 人类碳排放速率和升温速率很可能不仅在过去 6 600 万年内 (Zeebe *et al.*, 2016), 甚至在过去 2.52 亿年中都是前所未有的. 未来地球表层海水的温度和 pH 值变化可能超过地质历史时期的变化幅度, 对人类社会的可持续发展构成威胁 (Ridgwell and Schmidt, 2010). 然而, 由于测年数据、温度指标和碳排放数值模拟参数都存在误差和局限, 使得深时温度变化速率和碳排放速率的计算存在较大不确定性, 这为古今对比增加了复杂性 (图 6).

5 总结与展望

综上所述, 近年来的高精度测年数据和高分辨

率地质记录表明,西伯利亚大火成岩省和环特提斯洋及泛大陆周边的酸性大陆岩浆弧火山活动,可能都是二叠纪-三叠纪之交生物灭绝的关键驱动力。数值模拟和地质指标的综合分析逐步揭示了二叠纪-三叠纪之交的岩浆脱气产物种类繁多(CO_2 、 SO_2 、卤素和重金属元素等)且排放规模巨大(如碳排放达 $10^4 \sim 10^5$ Gt数量级)。这些规模庞大的脱气产物释放到地表系统中,诱发了一系列显著的环境效应,包括长期全球升温、海洋酸化、短期降温(火山冬天)、酸雨、臭氧层破坏以及重金属毒化等。这些环境效应在几个月到 10^5 年的不同时间尺度上,对海洋和陆地生态系统造成了严重破坏。高温、海洋缺氧与酸化等因素导致海洋生物的选择性灭绝,而陆地生态系统则面临臭氧层破坏、重金属毒化、火山冬天、酸雨及高温诱发的野火增多等多重环境压力。二叠纪-三叠纪之交火山活动及其引发的环境效应与生物响应,为当前全球变化问题提供了重要的历史借鉴,揭示了现代碳排放与升温速率可能已达到过去2.52亿年的最高水平。尽管近年来的研究显著加强了二叠纪-三叠纪之交火山活动与生物大灭绝之间联系的认识,但许多研究的不足仍限制了对二者关系的综合理解。以下几个方面仍需深入研究。

(1)提高碳排放过程定量估算的可靠性。一方面,建立更高分辨率的时间框架,减少 CO_2 地化数据和数值模拟边界条件的误差,以此进一步约束二叠纪-三叠纪之交碳排放的估算;另一方面,目前尚无法定量评估西伯利亚大火成岩省与酸性大陆岩浆弧火山活动在碳排放过程中的相对贡献大小。

(2)加强对岩浆脱气产物的研究。相较于 CO_2 和重金属,卤素和 SO_2 等脱气产物的地质证据十分薄弱,这导致部分环境效应与生物响应仍停留于理论推测中。未来需建立卤素和 SO_2 等脱气产物的新指标,用来探究二叠纪-三叠纪之交臭氧层破坏、酸雨及火山冬天等环境效应,并寻找相关生物响应的化石记录。

(3)深入研究环境效应与生物响应的空间与时间差异性。一方面,火山活动位置影响岩浆脱气产物的全球分布不均(如西伯利亚大火成岩省位于北半球),使短时间尺度的环境效应(如火山冬天、臭氧层破坏等)在火山活动周缘更为严重,可能导致不同地区生物灭绝强度或时间的差异;另一方面,长时间尺度的环境效应在不同地区也表现出差异(如高纬度升温更显著,陆地生态系

统对升温响应比海洋更敏感),进一步导致灭绝强度或时间的区域差异。未来需整合全球数据并结合海陆耦合地球系统模拟以剖析具体机制。

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