

峨眉山大火成岩省火山活动与中-晚二叠世之交生物灭绝的耦合关系

邓富昌

广西科技师范学院 职业技术教育学院, 广西 来宾 546199

摘要: 峨眉山大火成岩省(ELIP)火山活动与中-晚二叠世之交的生物灭绝事件间的耦合关系是地质学界研究的热点之一。基于前人研究成果,本文从古生物年代学、磁性地层学、同位素年代学等方面归纳了ELIP火山喷发起止时间,讨论了可能引起此次生物灭绝事件的成因机制,分析了ELIP火山活动与此次生物灭绝事件之间的内在联系。以上研究表明,ELIP火山喷发从260.55 Ma左右开始,至少持续到257.10 Ma左右,中-晚二叠世之交生物灭绝事件发生在约260~259 Ma,两者之间存在时空关联;另外,卡匹敦阶内 $\delta^{13}\text{C}_{\text{carb}}$ 约5‰的负偏移、相应牙形石带极低的 $^{87}\text{Sr}/^{86}\text{Sr}$ 值(0.7068~0.7070),以及瓜德鲁普统一乐平统过渡期的温度波动(4 °C升温后,6~8 °C变冷)等数据暗示ELIP火山活动与此次生物灭绝事件之间存在紧密联系,且ELIP火山喷发导致的气候变暖也能导致生物类群的选择性灭绝;大规模的海退、大洋缺氧、硫化海水上涌等可能是促进此次生物灭绝事件的重要因素。因此,ELIP火山活动可能严重影响海洋和陆地气候系统,是中-晚二叠世之交生物灭绝事件的主要驱动因素。

关键词: 峨眉山大火成岩省;生物灭绝;中-晚二叠世之交;年代学

中图分类号: P317, P597⁺, P52 文章编号: 1007-2802(2025)03-0662-14 doi: 10.3724/j.issn.1007-2802.20240152

The coupling relationship between volcanic activity of the Emeishan Large Igneous Province and the mass extinction at the turn of the Middle-Late Permian

DENG Fu-chang

College of Vocational and Technical Education, Guangxi Science & Technology of Normal University, Laibin Guangxi 546199, China

Abstract: The coupling relationship between the volcanic activity of the Emeishan Large Igneous Province (ELIP) and the mass extinction event at the turn of the Middle-Late Permian is one of the hot topics in the field of geological research. Based on previous researches, this article summarized the starting and ending times of the ELIP volcanic eruption from aspects of paleontology, magnetic stratigraphy and isotopic chronology, discussed the possible genetic mechanism of the mass extinction event and analyzed the internal relationship between the ELIP volcanic activity and the mass extinction event. The main conclusions drawn are as follows, the ELIP volcanic eruption began at about 260.55 Ma and lasted at least to about 257.10 Ma, and the mass extinction event occurred from 260 Ma to 259 Ma at the turn of the Middle-Late Permian. This means that there is a temporal and spatial correlation between the two events. In addition, characteristics of data such as the about 5‰ negative offset of $\delta^{13}\text{C}_{\text{carb}}$ values within the Capitanian stage, extremely low $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.7068~0.7070) of the corresponding conodont zones, and the temperature fluctuations during the Guadalupian-Lopingian transition period (the 4 °C warming followed by the 6~8 °C cooling) all suggest that there was a close connection between the ELIP volcanic activity and this mass extinction event. The selective extinction of some biological groups can be well explained by the climate warming caused by the ELIP volcanic eruption. Meanwhile, the large-scale seawater regression, oceanic water anoxia, and sulfidic seawater upwelling might be important factors contributing to this mass

收稿编号: 2024-0165, 2024-09-22 收到, 2025-01-17 改回

作者简介: 邓富昌(1987—), 男, 硕士, 工程师, 研究方向: 能源与气候环境效应. email: fuchangdeng@163.com

引用此文:

邓富昌. 2025. 峨眉山大火成岩省火山活动与中-晚二叠世之交生物灭绝的耦合关系. 矿物岩石地球化学通报, 44(3): 662–675

Deng F C. 2025. The coupling relationship between volcanic activity of the Emeishan Large Igneous Province and the mass extinction at the turn of the Middle-Late Permian. Bulletin of Mineralogy, Petrology and Geochemistry, 44(3): 662–675

extinction event. Therefore, the ELIP volcanic activity could have significantly affected the marine and terrestrial climate systems and was the main driving force caused the mass extinction event at the turn of the Middle-Late Permian.

Key words: Emeishan large igneous province; mass extinction; the turn of the Middle-Late Permian; chronology

0 引言

大火成岩省(large igneous province, LIP)是了解地球深处动力学过程和地表圈层演化之间联系的重要窗口(Chen and Xu, 2019)。在地球演化过程中, LIP火山活动发挥了重要作用, 是全球气候变化和矿产资源形成的重要驱动因素之一。因此, LIP成为国内外地质学者的关注热点, 研究内容主要聚焦在其基本类型(Bryan and Ernst, 2008)、岩石成因(Xu et al., 2001)、形成时间及其对古环境和古气候的影响(Burgess and Bowring, 2015)等方面。已有研究表明, LIP火山作用与地球演化历史中多次生物灭绝事件存在紧密联系。例如, 生物多样性损失最大的二叠纪末期大灭绝事件与西伯利亚LIP的爆发在时间上相吻合(Payne and Clapham, 2012); 白垩纪末期的生物大灭绝与德干溢流玄武岩的喷发同步(Schoene et al., 2019)。因此, 主流观点认为, LIP火山活动是导致大规模生物灭绝的主要因素之一(Clapham and Renne, 2019; Ernst et al., 2021)。

古生物研究表明, 二叠纪发生了两次显著的生物灭绝事件(Zhou et al., 2002)。其中, 二叠纪末期(PTB)生物灭绝事件是显生宙以来规模最大的一次生物灭绝事件(Wu et al., 2024)。而中-晚二叠世(瓜达鲁普世-乐平世[Guadalupian-Lopingian(G-L)]之交的生物灭绝事件对生物造成的影响虽没有二叠纪末灭绝事件那么严重, 但也是公认的地质历史时期大规模灭绝事件之一(Rampino and Shen, 2019)。该灭绝事件修正了古生代末生物多样性分布图谱的形态细节(童金南, 2021)。然而, 目前学术界对于诱发此次生物灭绝事件的具体原因还存在很大的争议。虽然有学者指出, 峨眉山火山活动可能是引起此次生物灭绝事件的原因(He et al., 2007), 但也有学者认为, 此次灭绝事件可能与海平面下降(Qiu et al., 2014)、硫化海上涌(Zhang et al., 2015; 张桂洁, 2016)、大洋缺氧(Wei et al., 2016)等事件有关。因此, ELIP火山活动与其他的生物灭绝驱动机制之间是否存在内在联系, 目前尚缺乏统一认识, 有待进一步的深入研究。

本文在对中-晚二叠世之交生物灭绝事件发生时间、影响范围、严重程度等进行总结分析的基础上, 结合前人最新研究成果, 对ELIP岩浆活动的持续和停止

时间等存在争议的问题进行讨论和归纳。基于ELIP年代学研究进展, 尝试建立ELIP与中-晚二叠世之交生物灭绝事件之间的时空联系。并在此基础上, 通过对引起中-晚二叠世之交生物灭绝事件的不同成因机制进行分析, 讨论ELIP与其他不同成因机制之间可能存在的内在联系, 以探究ELIP与此次生物灭绝事件之间的耦合关系, 进而为了解地球深部岩浆活动对表生生物活动的影响提供参考。

1 峨眉山大火成岩省概况

ELIP与俄罗斯境内西伯利亚溢流玄武岩齐名, 是国际地学界公认的大火成岩省之一。其喷发也被称为是瓜德鲁普统与乐平统界线处标志性的地质事件(刘宣威等, 2023)。溢流玄武岩是ELIP的标志性特征, 但超镁铁质和硅质火山岩以及层状镁铁质-超镁铁质和长英质深成岩也是其组成部分(Shellnutt, 2014)。其中, 玄武质岩浆的分离结晶是长英质岩形成的主要机制(Xu et al., 2010)。峨眉山玄武岩出露面积约 $2.5 \times 10^5 \text{ km}^2$, 总体积约 $0.3 \times 10^6 \text{ km}^3$ (Xu et al., 2001)。ELIP主要位于中国西南部云南、广西、贵州、四川等地区以及越南北部地区, 主体分布在哀牢山/红河断裂以北和龙门山断裂两侧(图1), 东北界到达成都一带。

野外地质调查显示, 与ELIP相关的火山岩一般不整合地覆盖在中二叠统茅口组灰岩之上(图2a、2b), 并被上二叠统或三叠系地层所覆盖(图2c)。ELIP火山序列西部较厚, 向东部和北部变薄(Zhu et al., 2018)。在丽江和织金地区可见玄武岩发育柱状节理(图2d、2e), 而宝兴地区可观察到峨眉山玄武岩发育枕状构造(图2f)。根据茅口组的侵蚀程度, 可将ELIP分为内、中、外带三个区域(Xu et al., 2004; 陈琦等, 2020)。根据 TiO_2 含量和Ti/Y值可以将峨眉山玄武岩进一步划分为高钛玄武岩和低钛玄武岩两类, 它们可能来自不同的地幔源, 在不同的熔融条件下, 经历了不同的分异和污染过程(Xu et al., 2001)。其中, 低钛玄武岩局限于ELIP的西部, 并被高钛玄武岩所覆盖(Ali et al., 2005)。

ELIP的形成一般被认为与地幔柱活动有关, 是地幔柱与岩石圈相互作用的产物(Xu et al., 2001; 张招崇等, 2005)。相关研究表明, 峨眉山地幔柱的轴部位置可能位于云南丽江一带(何冰辉, 2016)。部分学者认为华南板块西缘的古特提斯分支洋俯冲作用也可能对

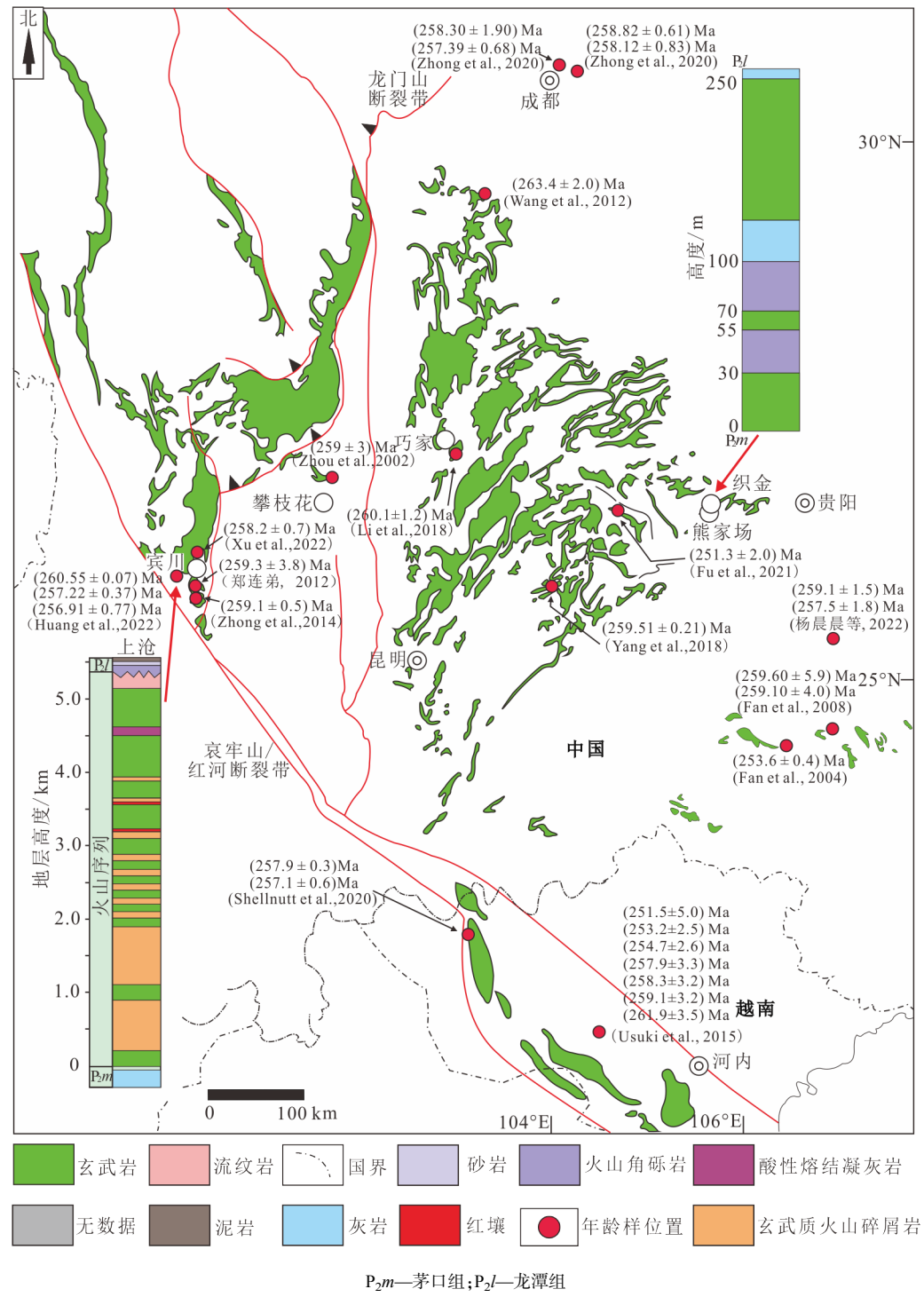


图1 峨眉山玄武岩分布范围图(据Thomas et al.,1998; Xu et al.,2001; Shellnutt et al.,2020; Huang et al.,2022修改)
Fig.1 Spatial distribution of the Emeishan basalt (modified from Thomas et al.,1998;Xu et al.,2001;Shellnutt et al.,2020; Huang et al.,2022)

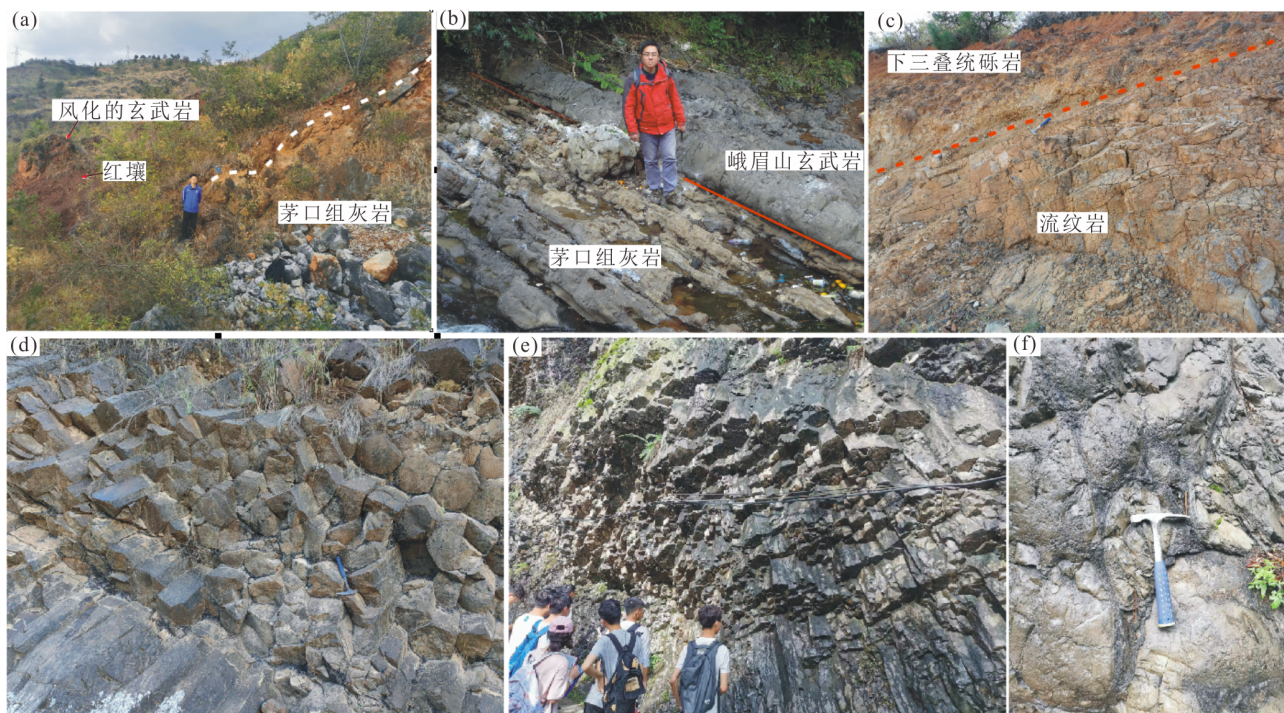
ELIP的形成和演化产生了一定的影响(Xu et al., 2019;Zhu B et al.,2021)。

2 中-晚二叠世之交生物灭绝事件

2.1 灭绝事件发生时间

中-晚二叠世之交生物灭绝事件最早是从中国南

方较大的底栖有孔虫记录中发现的(Jin et al.,1994), 其主要的信息来自潘基亚超大陆周围特提斯陆架地区的浅海沉积岩,特别是有丰富化石记录的华南地区海相碳酸盐岩(Ota and Isozaki.,2006)。部分学者根据对牙形石带年龄的估计,认为此次生物危机发生时间从卡匹敦阶*Jinogondolella shannoni*-*Jinogondolella*



(a)(b)挖色和织金地区峨眉山玄武岩与下伏中二叠统茅口组灰岩不整合接触(据Huang et al., 2019, 2022); (c)上沱地区与ELIP相关的流纹岩与上覆下三叠统砾岩呈不整合接触(据Huang et al., 2022); (d)(e)丽江和织金地区峨眉山玄武岩发育柱状节理; (f)宝兴地区峨眉山玄武岩发育枕状构造

图2 峨眉山玄武岩与地层接触关系及野外产状

Fig. 2 Contact relationships between the Emeishan basalt and strata and their field occurrences

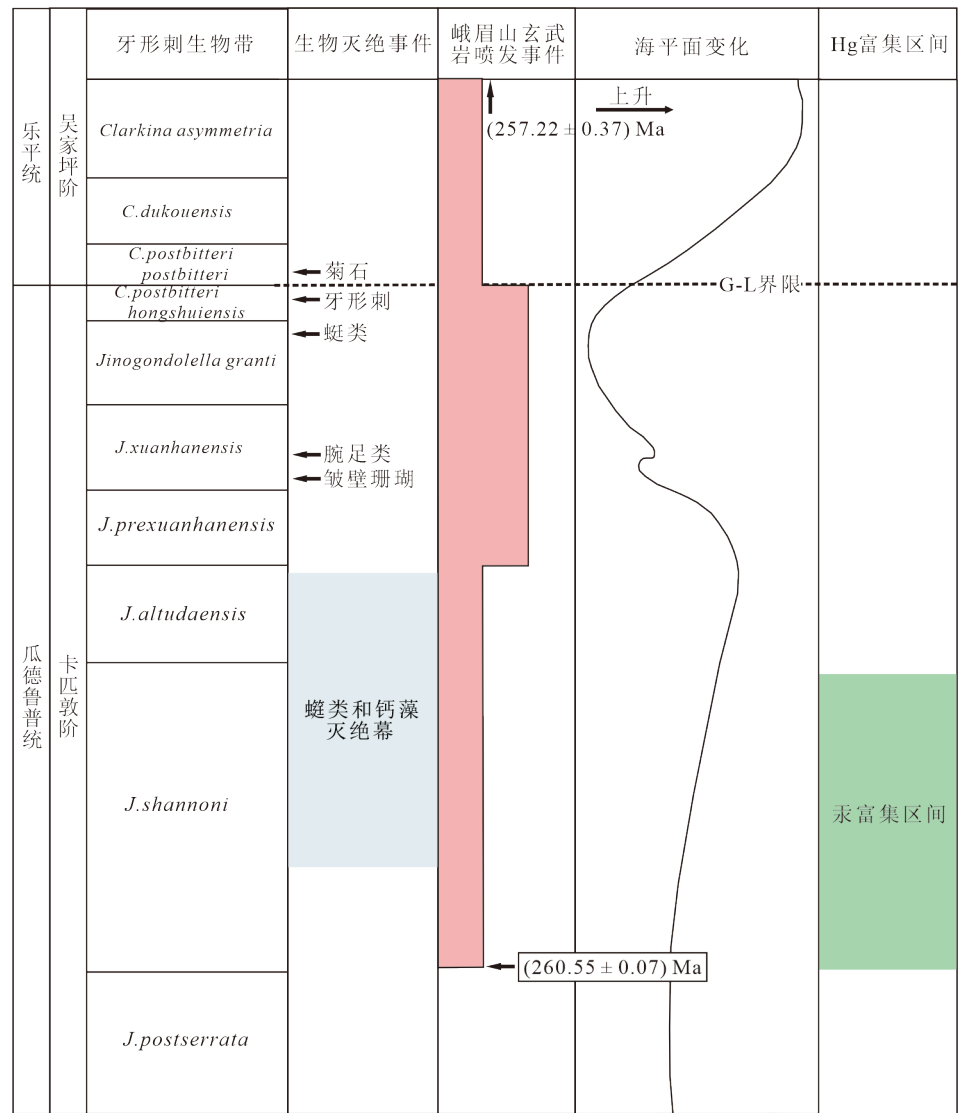
altudaensis 牙形石带界线附近开始(图3), 可能持续到晚二叠世早期 *Clarkina postbitteri postbitteri* 牙形石带, 对应年龄在约260~259 Ma之间(Wignall et al., 2009; Wu et al., 2020)。有学者通过对广西来宾蓬莱滩剖面中-晚二叠世界线附近地层的研究, 发现腕足类动物的组合被夹在 *Jinogondolella xuanhanensis* 和 *Jinogondolella granti* 两个牙形石带之间, 它们在年代上可以被认定为卡匹敦阶晚期(图3; Shen and Shi, 2009)。更重要的是, 这项研究认为先前认为的前乐平世腕足类动物的危机以及随后的复苏应发生在卡匹敦阶晚期, 即在中-晚二叠世界线之下(Shen and Shi, 2009)。这些生物多样性的损失最初认为发生在瓜德鲁普统-乐平统(G-L)边界附近, 而卡匹敦阶(Capitanian)是瓜德鲁普统最上部的一个阶(沈树忠等, 2018)。因此, 部分文献使用“瓜德鲁普世末期灭绝”或“卡匹敦阶灭绝”等来表示这次灭绝事件(Shen and Shi, 2009; Bond et al., 2020)。

2.2 灭绝事件对生物的影响

这次灭绝经历了群落的饮食比例、体型和动物群更替的巨大变化(Sahney and Benton., 2008)。灭绝层位也与整个北半球海相碳酸盐岩的消失相一致(Bond et al., 2015)。前人研究发现, 瓜德鲁普末期的大灭绝具有分类选择性(Chen and Xu, 2019), 而且对某些热

带生物群具有高度选择性(Arefifard and Payne., 2020)。其影响范围不但包括低纬度地区的热带海洋生物, 还包括北半球冷水无脊椎生物, 为一场真正的全球大规模灭绝(Bond et al., 2015), 与潘基亚超大陆形成时期的其他大规模灭绝具有可比性(Bond et al., 2020)。此外, 本次生物灭绝事件还导致了在南非Karoo盆地等关键地区长期较低的物种丰度(Day et al., 2018)。

相关估计表明, 瓜德鲁普事件导致大约71%的海洋物种消失(Stanley and Yang, 1994), 不同程度地影响了各种海洋无脊椎动物, 如珊瑚、腕足动物、软体动物和苔藓动物等(Chen and Shen, 2021)。在全球范围内, 蠕类经历了 $67\% \pm 4.6\%$ 的灭绝, 而非蠕类则经历了 $37\% \pm 5.7\%$ 的灭绝(Bond and Wignall, 2009)。物种损失最大的是在高纬度地区, 其中, 有孔虫仅在纬度相对较低的东格陵兰海道仍存在明显的多样性(Bond and Wignall, 2009)。在瓜德鲁普统内记录的43个非蠕类属在古特提斯洋和全球层面的灭绝程度分别为 $44\% \pm 3.3\%$ 和 $21\% \pm 2.7\%$ (Bond and Wignall, 2009)。在二叠纪中晚期的北半球Spitsbergen地区, 腕足类动物发生了两次严重的灭绝, 而第一次危机发生在卡匹敦阶内(Bond et al., 2015), 为此次生物灭绝事件对腕足动物造成影响提供了更多证据。在中二叠纪的茅口末期或



蜓类和钙藻灭绝幕据Wignall等(2009)；ELIP火山喷发年龄及界限据Huang等(2022)；汞富集区间据Huang等(2024)

图3 中-晚二叠世之交牙形刺生物带及其相应的生物灭绝事件和古环境变化(据韦雪梅等,2016及相关文献修改)
Fig.3 The conodont biozones at the turn of the Middle-Late Permian and its corresponding mass extinction event, as well as the palaeo-environmental changes (modified from Wei et al., 2016 and related literature revisions)

接近末期,腕足类动物的多样性和丰富度出现急剧下降,占87%的物种发生灭绝(Shen and Shi,1996)。这场危机不仅导致有孔虫类和腕足类的严重灭绝,也导致中国南方钙质藻类和其他浅水类生物群的显著更替(Bond et al.,2010a)。菊石的灭绝相对较晚,顶峰发生在吴家坪阶的最早期阶段(Villier and Korn,2004)。通过统计分析,珊瑚有75.6%的科、77.8%的属和82.2%的种在该事件中消失(Wang and Sugiyama,2000)。而有孔虫、双壳类和腹足类动物在科和属水平上在此次生物危机事件中则没有发生明显变化(Jin et al.,1994)。对于瓜德鲁普末期海相生物总的灭绝率还缺少统一的认识。多数学者认为瓜德鲁普末期海相生物属的总灭绝率为36%~47%(Sepkoski,1996;Bambach

et al.,2004)。
中-晚二叠世之交生物灭绝事件不仅对部分海洋生物造成了影响,也导致了陆地生物系统的破坏和毁灭。该时期,陆地植物类群也发生了重大转变(Rampino and Shen,2019)。其中,华南地区的植物化石记录显示,卡匹敦阶陆相物种损失高达24%(Bond and Wignall,2014)。华北克拉通中56%的植物灭绝也可能与此次生物危机事件相关(Bond et al.,2010b)。此次生物危机事件也对陆生脊椎动物造成了影响(Day et al.,2018)。有学者基于南非Karoo盆地化石数据研究,认为中二叠纪末期的陆地灭绝也是一个重大事件,其造成四足类动物群经历了74%~80%的属丰富度损失(Day et al.,2015)。

3 峨眉山大火成岩省年代学研究进展及认识

近年来,众多学者将古生物年代学、磁性地层学、同位素年代学等方法用于限定ELIP岩浆活动的开始年龄及持续时间,取得了丰硕研究成果,为限制ELIP的活动时间提供了依据。

3.1 古生物年代学约束

前人在峨眉山溢流玄武岩下伏中二叠统茅口组灰岩中发现了*Yabeina-Neomisellina*带蠕类化石,据此认为ELIP初始喷发时间不早于中二叠世晚期(He et al., 2003)。贵州织金地区保存了一套完整的火山-沉积序列(图1),该序列主要由两套峨眉山玄武岩及火山角砾岩夹灰岩组成(Wignall et al., 2009; Sun et al., 2010; Bond et al., 2010a)。其中,在底部玄武岩之下灰岩中发现了*J. altudaensis*牙形石带(Sun et al., 2010),该牙形石带所指示的碳酸盐岩台地崩塌被认为与ELIP火山活动有关(Sun et al., 2010; Wignall et al., 2009)。因此,ELIP喷发时间应该不晚于*J. altudaensis*牙形石带形成时间。

ELIP火山喷发初期可能造成华南西南部部分地区隆升并造成下伏地层普遍缺失(Ali et al., 2010; He et al., 2003),受峨眉山幔柱上升造成的地壳快速差异抬升,以及瓜德鲁普世末期全球范围内的大规模海平面下降影响,这为生物地层精细约束带来一定困难(陈军和徐义刚, 2017)。部分学者利用牙形石生物地层学,对华南猫儿山和朝天剖面瓜德鲁普统-乐平统边界(GLB)周围火山灰开展研究,推断ELIP的主要阶段发生在约260.9~259.1 Ma,最早的喷发发生在约263.5 Ma(Zhong et al., 2020)。而在随后的研究中,牙形石年龄估算模型暗示ELIP初始喷发时间在260 Ma左右(Wu et al., 2020)。峨眉山玄武岩之上一般为上二叠统宣威组龙潭组和三叠纪碎屑岩所覆盖(He et al., 2003),缺少有效的生物化石约束其终止年龄。但牙形石带和火山灰年龄的对比研究结果显示,ELIP火山活动至少可以持续到*Clarkina orientalis*牙形石带底部,对应年龄在257.8 Ma左右(Shen et al., 2011; Huang et al., 2018)。

3.2 磁性地层学年代约束

磁性年代学研究结果显示,云南东北部以及四川盐源、峨边等地区峨眉山玄武岩的喷发可分为早期的正极性期和晚期的反极性期(Ali et al., 2002; Zheng et al., 2010)。其中,代表早期火山喷发的正极性带对应中二叠世晚期的正极性带(Hounslow and Balabanov, 2018; Shen et al., 2019)。宾川位于ELIP的西部,该地

区保存有厚达5300 m的大火成岩省火山序列(图1; Xu et al., 2001; Huang et al., 2022)。该剖面火山序列中,下部主要由碎屑熔岩组成,中部以斑状玄武岩为主,上部为富斑玄武岩(Zhong et al., 2014)。前人研究发现,宾川剖面中正极性带火山岩序列最底部还存在反极性带,暗示宾川地区可能记录了最早的火山喷发(Xu et al., 2022)。而磁性年代学研究结果显示,峨眉山玄武岩的喷发年龄很可能是在(259.3±3.8) Ma(郑连弟, 2012)。结合磁性地层年龄研究结果,ELIP的持续喷发时间一般被认为小于3 Ma(Zheng et al., 2010; Liu et al., 2012)。

3.3 Ar-Ar同位素年代学约束

21世纪初,研究人员通过对峨眉山火山岩和侵入岩进行全岩及单矿物(角闪石和黑云母) $^{40}\text{Ar}/^{39}\text{Ar}$ 定年,认为峨眉山岩浆活动的主要阶段发生在253~251 Ma的短暂时期,而早期火山活动则发生在~255 Ma(Lo et al., 2002)。在随后的研究中,有学者对广西西部晚古生代玄武岩样品进行 $^{40}\text{Ar}/^{39}\text{Ar}$ 和SHRIMP锆石U-Pb定年,并结合已公布的ELIP年龄数据,约束ELIP火山喷发开始时间为~260 Ma,在256~253 Ma之间大量爆发,结束时间约为253~251 Ma(Fan et al., 2004)。近年来,部分学者获得云南巧家县高钛玄武岩中斜长石的 $^{40}\text{Ar}/^{39}\text{Ar}$ 年龄为(260.1±1.2) Ma,并认为该年龄可以代表ELIP高钛玄武岩开始喷出的时间(Li et al., 2018)。综合研究表明,不同实验室新的 $^{40}\text{Ar}/^{39}\text{Ar}$ 年龄数据将巧家高钛玄武岩样品的年龄进一步约束在(259.9±0.9) Ma(Jicha et al., 2019)。

3.4 锆石U-Pb同位素年代学约束

锆石U-Pb定年技术主要包括激光剥蚀电感耦合等离子体质谱仪(LA-ICP-MS)、二次离子质谱仪(SIMS)和化学磨蚀同位素稀释热电离质谱(CA-ID-TIMS)等(李献华等, 2022)。有学者最早对川南攀枝花地区镁铁质侵入岩分离出来的锆石获得(259±3) Ma的U-Pb年龄(Zhou et al., 2002)。随后的二十多年中大量有关ELIP的锆石U-Pb年龄数据被报道(图4),这些年龄从(266±5) Ma变化到(238±3) Ma(Chen and Xu, 2019)。然而,这些年龄数据大多是基于LA-ICPMS或SIMS方法获得的,存在较大的误差(1%~4%)(李献华等, 2015),这也是限定ELIP岩浆活动时间需要考虑的因素。前人对越北地区同一花岗岩和流纹岩样品中的锆石开展LA-ICPMS和CA-ID-TIMS方法测试,分别获得(254±2)~(246±3) Ma和(257.9±0.3)~(256.3±0.4) Ma两种完全不同的年龄结果(Shellnutt et al., 2020; Pham et al., 2022),反映了高精度年代学测试在

ELIP年代学研究中的重要性。

云南宾川地区ELIP火山序列上部酸性熔结凝灰岩化学磨蚀热电离子质谱法(CA-TIMS)锆石U-Pb年龄显示,峨眉山溢流玄武岩的主喷发结束年龄为 (259.1 ± 0.5) Ma (Zhong et al., 2014)。该年龄与贵州普安火山岩顶部凝灰岩CA-TIMS锆石U-Pb年龄一致 (259.51 ± 0.21) Ma, 而比四川上寺、朝天以及湖北猫儿山ELIP凝灰岩的高精度年龄(约258~257 Ma)老(Huang et al., 2018; Yang et al., 2018; Zhong et al., 2020)。越南北部沱江地区ELIP相关的流纹岩高精度年龄在 $(257.9 \pm 0.3) \sim (257.1 \pm 0.6)$ Ma之间(Shellnutt et al., 2020), 进一

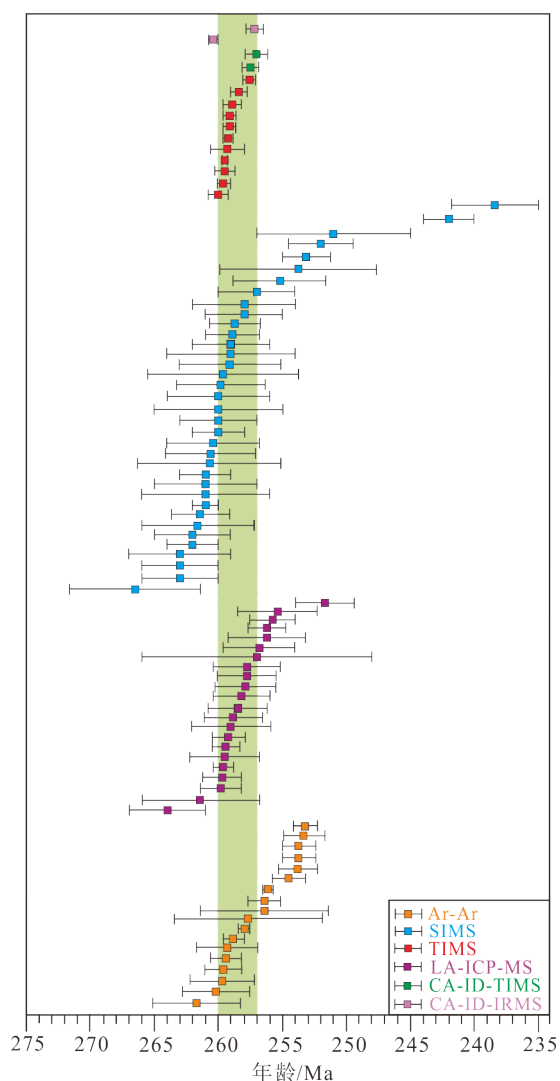
步暗示ELIP火山活动可以持续到晚二叠世早期。而对宾川地区火山序列顶部样品高精度U-Pb锆石化学磨蚀-同位素稀释-同位素比值质谱(CA-ID-IRMS)数据研究表明, ELIP火山喷发从 (260.55 ± 0.07) Ma开始, 并至少持续到 (257.22 ± 0.37) Ma (Huang et al., 2022), 与四川攀枝花和越南北部沱江地区ELIP侵入岩年龄 $(259.5 \pm 0.8) \sim (256.3 \pm 0.4)$ Ma在误差范围内基本接近(Shellnutt et al., 2012, 2020)。对于ELIP喷发起始时间, 研究结果则比较接近, 集中分布在260 Ma左右(Fan et al., 2004; Li et al., 2018; Wu et al., 2020; Huang et al., 2022)。而对于ELIP火山喷发结束时间, 目前所得年龄结果变化范围较大, 主要分布在259~251 Ma之间(图4)。前人通过对已有年龄数据统计发现, 目前高精度定年获取的ELIP活动年龄大致在260~257 Ma之间, 而较早Ar-Ar、SIMS和LA-ICP-MS定年结果在误差范围内也多集中在260~255 Ma内(图4)。但需注意的是, 包括普安和宾川在内的很多剖面顶部的火山岩均与上覆地层为平行不整合接触, 这可能与ELIP火山喷发结束后遭受到的强烈风化剥蚀作用有关(He et al., 2007; Yang et al., 2015; Huang et al., 2022)。257.10 Ma可以指示ELIP结束时间下限, 同时也表明ELIP火山活动持续时间应不晚于3 Ma。

4 峨眉山大火成岩省与中-晚二叠世之交生物灭绝事件的耦合关系

基于高精度U-Pb定年结果和牙形石带对比, 前人逐步认识到全球LIP与大规模生物灭绝事件之间存在密切联系(图5)。而对于ELIP与中-晚二叠世之交生物灭绝事件之间的关系, 有学者通过高精度年代学研究提出峨眉山火山活动略早于中-晚二叠世之交生物灭绝事件的开始(Huang et al., 2022)。而且, 南非地区陆相四足类动物群灭绝时间被约束在 (260.259 ± 0.081) Ma, 略晚于ELIP的初始喷发时间(图6), 也支持ELIP火山活动与中-晚二叠世之交陆相生物灭绝事件在时间上存在联系(Day et al., 2015)。贵州熊家场剖面生物灭绝伴随的碳酸盐岩台地崩塌也被认为与ELIP火山活动有关(Wignall et al., 2009)。但随之而来的问题是, 中-晚二叠世之交生物灭绝事件发生的诱因是什么, ELIP火山喷发是否能够引起广泛的水陆环境变化, 并最终导致大规模的生物灭绝。

4.1 引起中-晚二叠世之交生物灭绝的潜在诱因

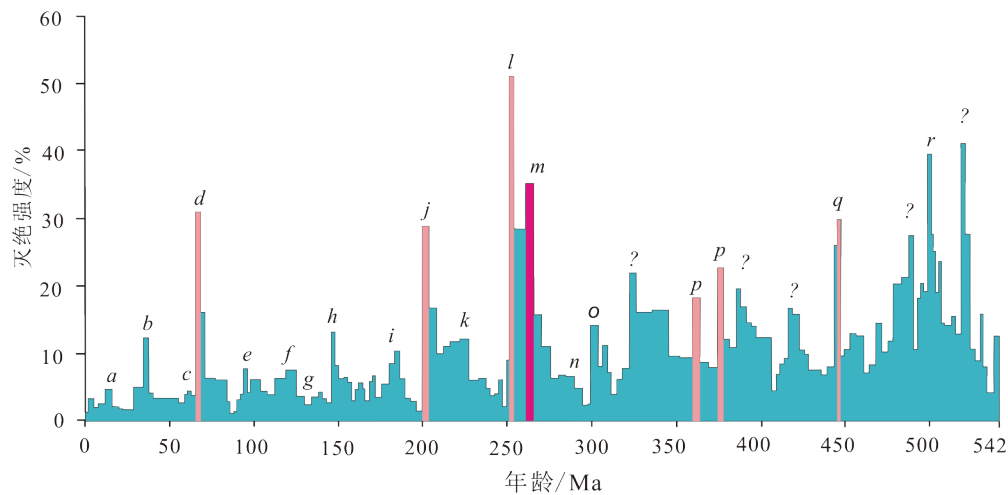
4.1.1 大规模海退 前人研究认为, 中-晚二叠世之交发生的短暂大规模海退作用在生物灭绝中扮演了重要的角色(Isozaki et al., 2008; Qiu et al., 2014)。研究人员在熊家场剖面*J. prexuanhanensis*–*J. xuanhanensis*



高精度年龄数据来源: Jicha等(2019); Shellnutt等(2020); Fu等(2021)和Huang等(2022); 其他年龄汇总于Chen和Xu(2019)

图4 ELIP喷出岩和侵入岩已发表的地质年龄数据汇总
(据Chen and Xu, 2019修改)

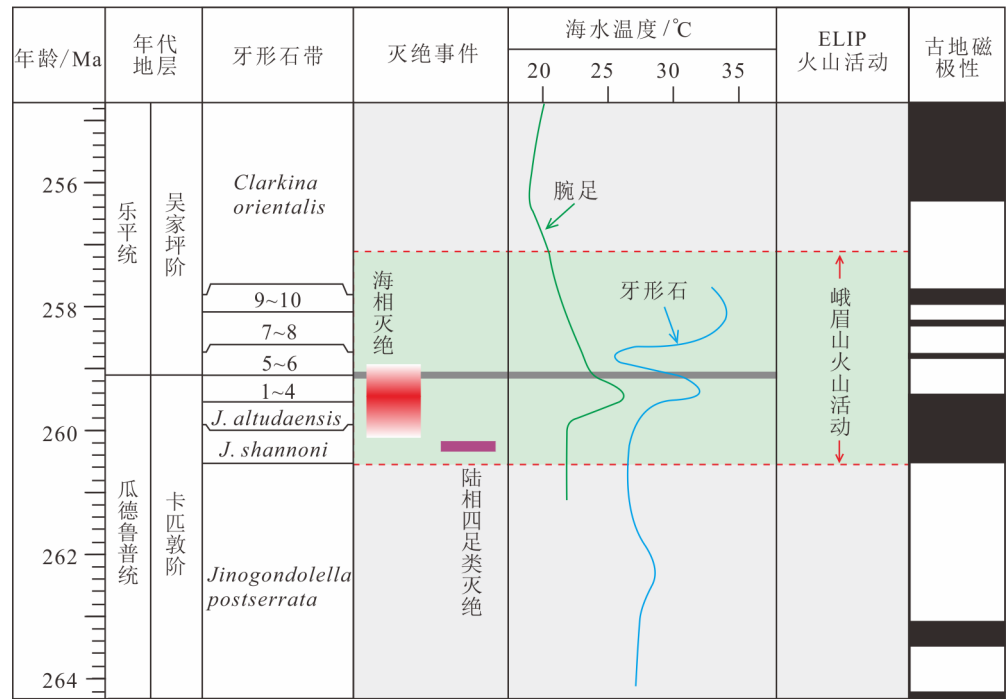
Fig.4 Summary of published geochronological data from the ELIP eruptive and intrusive rocks (modified from Chen and Xu, 2019)



a—哥伦比亚河大火成岩省(16.5 Ma), 对应始新世末生物灭绝;b—Afar(32~29 Ma);c—北大西洋大火成岩省(62~54 Ma);d—德干大火成岩省(66 Ma), 对应白垩纪末生物灭绝;e—Carrigan, Madagascar & others (c.93 Ma);f—翁通爪哇大火成岩省和其他(120 Ma);g—巴拉那与伊藤达卡大火成岩省(132 Ma);h—N.Aust.Margin, Shatsky Rise & others (c.150 Ma), 对应侏罗纪末生物灭绝;i—南非大火成岩省(183~179 Ma);j—中大西洋岩脊省(201 Ma), 对应三叠纪末生物灭绝;k—Wrangellia(225 Ma);l—西伯利亚暗色岩(252Ma), 对应二叠纪末生物灭绝;m—峨眉山大火成岩省(259 Ma), 对应中二叠世末灭绝事件;n—塔里木(c.285 Ma);o—Skagerrak(300 Ma);p—Kola-Dnieper和Yakutsk-Vilyui(c.380~360 Ma), 对应晚泥盆世生物灭绝;q—? Suodakh and others(c. 440 Ma), 对应奥陶纪末生物灭绝;r—Kalkarindji(510 Ma)

图5 大火成岩省火山活动与显生宙生物灭绝事件的相关性(据Ernst and Youbi,2017修改)

Fig.5 Correlation between volcanic activities of large igneous provinces and Phanerozoic mass extinction events (modified from Ernst and Youbi,2017)



1—*J. prexuanhanensis*;2—*J. xuanhanensis*;3—*J. granti*;4—*C. postbitteri hongshuiensis*;5—*C. postbitteri postbitteri*;6—*C. dukouensis*;7—*C. asymmetrica*;8—*C. leveni*;9—*C. guangyuanensis*;10—*C. transcaucasica*;J—*Jinogondolella*; C—*Clarkina*。古地磁极性图中,黑色代表正磁异常,白色代表负磁异常

图6 GLB附近的主要地质事件(据Huang et al.,2022修改)

Fig.6 Major geological events close to the Guadalupian-Lopingian boundary(modified from Huang et al.,2022)

牙形带内,发现深水缺氧的硅质岩之上突然出现浅水台地碳酸盐岩,暗示发生了一次重大的海平面下降事件(Bond et al.,2010a)。而且,海平面低位出现的时间

与来宾铁桥*Jinogondolella granti*牙形刺带消失的时间相一致(Chen et al.,2009;图3)。海平面下降会引起浅海生物生存空间减少,进而影响其生存环境。然而,部

分学者认为中-晚二叠世之交的海退主要发生在*J. xuanhanensis*牙形石带之后(Wignall et al., 2009), 并不能为中-晚二叠世之交最早期的生物灭绝事件做出解释。而且, 一些大规模海退并没有导致明显的生物灭绝事件(韦雪梅等, 2016)。结合中-晚二叠世之交陆地生物也发生了大量的灭绝这一事实, 我们认为大规模海退作用可能不是导致此次生物灭绝事件的主要原因。

4.1.2 海洋缺氧 在G-L转变过程中的第一个生物地层 $\delta^{34}\text{S}_{\text{sulfate}}$ 值出现先剧烈负移, 然后快速正移的变化过程, 范围为36.88‰~37.41‰, 表明在G-L转变期间的海洋出现了有氧浅水与缺氧深水分层现象(Yan et al., 2013)。深水缺氧水域的形成和进一步扩散, 会缩小海洋生物栖息地范围, 这可能是引起海洋生物多样性减少的原因之一。而卡匹敦阶海洋表层生产力的增加, 促进了氧最小区(OMZ)的扩大(Saitoh et al., 2014), 从而进一步对浅海生物造成影响。海洋缺氧通常被认为能够引起海洋生物危机, 但其能否引起某些生物群高度选择性灭绝也是值得思考的问题。学者研究发现, 虽然中-晚二叠世之交生物灭绝期间涉及海洋缺氧的情景得到了Kapp-Starostin最深水域黄铁矿和微量金属地球化学数据的支持, 但它无法解释不缺氧的地区仍然发生了物种灭绝(Bond et al., 2015)。因此, 海洋缺氧可能不是唯一引起此次生物灭绝事件的原因。

4.1.3 硫化海水上涌 有研究者利用多硫同位素手段研究中-晚二叠世之交生物灭绝事件发生期间海洋化学条件的变化, 结果发现在中国和美国瓜德鲁普统上部地层中大量出现负的 $\Delta^{33}\text{S}$ 值(约-0.095‰~-0.028‰), 因此认为当时硫化海水上涌具有广泛性(张桂洁, 2016)。硫化深水上升到浅层大陆架, 可能对浅海生物群造成了压力(Saitoh et al., 2014)。而来自中国南部和德克萨斯西部的硫同位素异常一致性表明, 硫化水域的广泛上涌和中-晚二叠世之交大灭绝之间存在因果关系(Zhang et al., 2015)。由于缺乏同时代的大洋中部信息, 目前尚不清楚硫化物水是在整个开阔海洋中扩张还是仅限于大陆边缘地带(Maruoka and Isozaki, 2020)。虽然多硫同位素研究结果为硫化海水上涌事件提供了有力支持, 但硫化海水具体的上涌机制还有待进一步的深入研究。

4.1.4 火山喷发导致的环境毒化 火山在喷发过程中, 常释放大量的二氧化硫、硫化氢、汞等有毒物质到大气中, 进而影响地球大气圈和水圈。在众多元素中, 汞的异常富集被认为可能与大规模火山活动有关(Grasby et al., 2016)。有研究者基于广西地区两个沿

海浅水区的汞浓度、汞同位素和有机碳同位素数据集, 发现在GLB的两个剖面中Hg/TOC比率升高, Hg含量与TOC的质量百分比比值分别高达3330($\times 10^{-9}/\%$)和221($\times 10^{-9}/\%$)和接近零至正的 $\Delta^{199}\text{Hg}$ 值(-0.04‰~+0.26‰), 这表明存在广泛的火山汞通过湿Hg(II)沉积进入海洋(Ling et al., 2023), 指示有大规模火山作用导致地球表层Hg的超常富集。从大规模火山活动中增加的汞通量可能会对陆地和海洋领域产生全球影响, 也可能是地球历史上一个重要的灭绝机制(Grasby et al., 2016, 2020)。目前, 中-晚二叠世之交的腕足类、珊瑚类和双壳类灭绝层位都记录到了异常的汞富集, 表明火山喷发可能引发了中-晚二叠世之交的生物灭绝事件(Huang Y G et al., 2019; Bond et al., 2020)。由此可见, 火山作用导致的有毒物质剧增, 也可能是导致中-晚二叠世之交生物灭绝的重要因素之一。

4.2 ELIP火山喷发引发的综合效应与中-晚二叠世之交生物灭绝

前人研究表明, 引起中-晚二叠世之交生物灭绝的原因可能不是单一的, 更像是某一事件所导致的综合效应。如前所述, 在地球演化过程中发生的历次大规模生物灭绝多与LIP在时间上存在一定耦合性(图5)。而近年来地球化学方面越来越多的证据表明, 中-晚二叠世之交生物灭绝可能是ELIP火山活动的结果。

研究人员通过跟踪卡匹敦阶碳系统的变化, 发现在*Jinogondolella postserrata*和*Jinogondolella altudaensis*区之间 $\delta^{13}\text{C}_{\text{carb}}$ 值从+2‰~+4‰, 然后出现约5‰的主要负偏移, 这与*J. altudaensis*区发生生物灭绝的初始阶段相吻合(Bond et al., 2010a)。前人通过总结, 发现此次生物灭绝事件期间, 碳同位素在中国出现较大偏移(高达-6‰)(Bond and Grasby, 2017)。峨眉山玄武岩的喷发可能引发了大量甲烷和二氧化碳的快速释放, 这可能是导致全球 $\delta^{13}\text{C}$ 漂移和相关环境危机的原因(Lo et al., 2002)。大量二氧化碳的释放能够引起温室效应, 进而引起地球温度的波动和海平面的变化。有学者基于O同位素的研究发现, 在卡匹敦阶中期, 方解石的 $\delta^{18}\text{O}$ 值下降了约1.0‰, 随后在吴家坪阶晚期逐渐上升了约2.0‰, 认为卡匹敦阶经历了先变暖, 而后变冷的气候变化历程(Wang et al., 2020)。有学者研究发现, 在瓜德鲁普统-乐平统转换期间, 发生了显著的温度波动(升温4℃, 后降温6~8℃)(Chen et al., 2013)。峨眉山玄武岩早期具有较高的喷发速率, 大约85%的体积在(1.45±0.50) Ma内喷发, 这可能是导致早期气候变暖的直接因素(Huang et al., 2022)。而ELIP晚期硅质火山活动可能对卡匹敦阶-吴家坪阶过渡期的全球冷却具有潜在影响(Zhu J et al.,

2021)。ELIP玄武岩的快速风化可能是引起吴家坪阶早期气候降温的重要因素(Huang et al., 2022)。

在许多假设的致死机制中,峨眉山溢流玄武岩火山作用引起的气候变暖最能解释携带共生体藻类的优先灭绝,以及可能具有相似组合的其他类群,如珊瑚和双壳类的选择性灭绝(Arefifard and Payne, 2020)。同时,温度升高还会使陆地生态系统中甲壳类生物的感官能力下降(沈树忠等, 2024),进而对生物生存造成影响。大气中温室气体增高除能够引起气候变暖外,还可以引起海洋酸化、碳酸盐浓度过高以及海洋缺氧等一系列问题(Bond and Grasby, 2017; Song et al., 2023)。峨眉山玄武岩枕状构造(图2f)的发育,表明ELIP存在一定量的海底喷发。而ELIP海底喷发可能引起海水化学性质发生变化(Yan et al., 2023)。在卡匹敦阶晚期的*Jinogondolella prexuanhanensis*-*J. xuanhanensis*中发现了极低的 $^{87}\text{Sr}/^{86}\text{Sr}$ 比值(0.7068~0.7070),对应于峨眉山火山喷发时间,而峨眉山玄武岩下的石灰岩具有较高的 $^{87}\text{Sr}/^{86}\text{Sr}$ 比值(0.7070~0.7074),表明 $^{87}\text{Sr}/^{86}\text{Sr}$ 出现最小值与ELIP爆发之间存在潜在联系(Huang et al., 2019)。有学者认为,ELIP的初始活动促进了卡匹敦阶中期深海OMZ的发展,导致卡匹敦阶晚期OMZ扩展到浅水平台(Kuang et al., 2024)。

也有一些学者在雄家场段发现Hg浓度出现较大的变化(2.40×10^{-9} ~ 210×10^{-9}),而且在*J. shannoni*牙形石带发现Hg富集区间(图3),这与ELIP火山活动开始时间相一致(Huang et al., 2024)。来自丹阳的地球化学数据表明, $\delta^{13}\text{C}_{\text{org}}$ 从底部到约60 m之间出现了明显的负偏移(5.8‰),而对于TOC>0.2%的情形,Hg浓度和Hg/TOC在45~81 m的区间也出现了峰值,负 $\delta^{13}\text{C}_{\text{org}}$ 偏移和同期Hg/TOC比出现显著峰值,这一发现支持峨眉山火山爆发向环境排放广泛汞负荷(Kwon et al., 2019)。以上证据也进一步表明,ELIP火山活动向大气输送了大量的温室气体和有毒物质。因此,ELIP火山迅速喷发可能导致气候变暖,并促进了海洋OMZ区间的扩展,加剧了海洋缺氧,不仅导致气候先暖后冷,还引起相对应的海平面升降变化。而硫化海水扩张以及ELIP火山喷发导致的环境毒化进一步加剧了环境恶化,最终引起海洋和陆地生物危机。ELIP火山喷发可能严重影响了中-晚二叠世之交的海洋和陆地气候系统,是此次生物灭绝事件的主要驱动因素。

5 结论

(1)中-晚二叠世之交生物灭绝事件不同程度地影响了海洋和陆地生物。此次生物危机从卡匹敦阶*Jinogondolella shannoni*-*Jinogondolella altudaensis*牙

形石带界线附近开始,并可能持续到了晚二叠世早期*Clarkina postbitteri postbitteri*牙形石带。此次灭绝经历了群落的饮食比例、体型和动物群更替的巨大变化,代表一场真正的全球大规模灭绝。但瓜德鲁普末期海相生物总的灭绝率还缺乏统一的认识,是未来研究方向之一。

(2)结合众多年代学研究成果,本文认为ELIP初始喷发时间在260.55 Ma左右,火山活动至少持续到257.10 Ma左右。结合前人高精度年代学定年结果分析可知,ELIP火山活动至少持续3 Ma。

(3)海退作用、硫化海水上涌、海洋缺氧等可能在此次生物灭绝事件中起到了重要作用,而峨眉山火山作用引起的气候和环境变化最能解释一些生物类群选择性灭绝问题。因此,从ELIP喷发时限及其引起的环境效应,可以看出ELIP与中-晚二叠世之交生物灭绝事件之间存在密切的耦合关系。

(4)目前有关引起中-晚二叠世之交生物灭绝的机制还主要停留在定性研究上,缺少定量模型的约束。相信随着定年技术、大数据以及机器学习等新兴学科不断发展,这些都将有助于更好地理解中-晚二叠世之交生物灭绝事件和ELIP之间的关系。

利益冲突声明: 作者保证本文无利益冲突。

致谢: 匿名审稿专家和编辑老师提出了大量宝贵意见和建议,在此表示由衷的感谢。

参考文献 (References):

- Ali J R, Fitton J G, Herzberg C. 2010. Emeishan large igneous province (SW China) and the mantle-plume up-doming hypothesis. *Journal of the Geological Society*, 167(5): 953–959
- Ali J R, Thompson G M, Song X Y, Wang Y L. 2002. Emeishan basalts (SW China) and the ‘end-guadalupian’ crisis: Magnetobiostratigraphic constraints. *Journal of the Geological Society*, 159(1): 21–29
- Ali J R, Thompson G M, Zhou M F, Song X Y. 2005. Emeishan large igneous province, SW China. *Lithos*, 79(3–4): 475–489
- Arefifard S, Payne J L. 2020. End-Guadalupian extinction of larger fusulinids in central Iran and implications for the global biotic crisis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 550: 109743
- Bambach R K, Knoll A H, Wang S C. 2004. Origination, extinction, and mass depletions of marine diversity. *Paleobiology*, 30(4): 522–542
- Bond D P G, Grasby S E. 2017. On the causes of mass extinctions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 478: 3–29
- Bond D P G, Wignall P B. 2009. Latitudinal selectivity of foraminifer extinctions during the late Guadalupian crisis. *Paleobiology*, 35(4): 465–483
- Bond D P G, Wignall P B, Wang W, Izon G, Jiang H S, Lai X L, Sun Y D, Newton R J, Shao L Y, Védérine S, Cope H. 2010a. The mid-Capitanian (Middle Permian) mass extinction and carbon isotope record of South

- China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 292(1–2): 282–294
- Bond D P G, Hilton J, Wignall P B, Ali J R, Stevens L G, Sun Y D, Lai X L. 2010b. The Middle Permian (Capitanian) mass extinction on land and in the oceans. *Earth-Science Reviews*, 102(1–2): 100–116
- Bond D P G, Wignall P B. 2014. Large igneous provinces and mass extinctions: An update. *Volcanism, impacts, and mass extinctions: causes and effects*, 505: 29–55
- Bond D P G, Wignall P B, Joachimski M M, Sun Y D, Savov I, Grasby S E, Beauchamp B, Blomeier D P G. 2015. An abrupt extinction in the Middle Permian (Capitanian) of the Boreal Realm (Spitsbergen) and its link to anoxia and acidification. *Geological Society of America Bulletin*, 127(9–10): 1411–1421
- Bond D P G, Wignall P B, Grasby S E. 2020. The capitanian (guadalupian, Middle Permian) mass extinction in NW pangea (borup fiord, Arctic Canada): A global crisis driven by volcanism and anoxia. *GSA Bulletin*, 132(5–6): 931–942
- Bryan S E, Ernst R E. 2008. Revised definition of large igneous provinces (LIPs). *Earth-Science Reviews*, 86(1–4): 175–202
- Burgess S D, Bowring S A. 2015. High-precision geochronology confirms voluminous magmatism before, during, and after Earth's most severe extinction. *Science Advances*, 1(7): e1500470
- Chen B, Joachimski M M, Shen S Z, Lambert L L, Lai X L, Wang X D, Chen J, Yuan D X. 2013. Permian ice volume and Palaeoclimate history: Oxygen isotope proxies revisited. *Gondwana Research*, 24(1): 77–89
- Chen J, Shen S Z. 2021. Mid-Permian (end-guadalupian) extinctions. In: *Encyclopedia of Geology*. Amsterdam: Elsevier: 637–644
- Chen J, Xu Y G. 2019. Establishing the link between Permian volcanism and biodiversity changes: Insights from geochemical proxies. *Gondwana Research*, 75: 68–96
- 陈军, 徐义刚. 2017. 二叠纪大火成岩省的环境与生物效应: 进展与前瞻. *矿物岩石地球化学通报*, 36(3): 374–393 [Chen J, Xu Y G. 2017. Permian large igneous provinces and their impact on paleoenvironment and biodiversity: Progresses and perspectives. *Bulletin of Mineralogy, Petrology and Geochemistry*, 36(3): 374–393 (in Chinese with English abstract)]
- 陈琦, 于宋月, 温汉捷, 蓝江波, 罗重光. 2020. 滇东-黔西地区峨眉山玄武岩 Nb-Ga-REE富集机制及赋存状态初步研究. *矿物岩石地球化学通报*, 39(6): 1256–1277 [Chen Q, Yu S Y, Wen H J, Lan J B, Luo C G. 2020. A preliminary study on the possible mechanism of enrichment and occurrence state of Nb-Ga-REE in the Emeishan basalts from the Diandong-Qianxi Region. *Bulletin of Mineralogy, Petrology and Geochemistry*, 39(6): 1256–1277 (in Chinese with English abstract)]
- Chen Z Q, George A D, Yang W R. 2009. Effects of Middle–Late Permian sea-level changes and mass extinction on the formation of the Tieqiao skeletal mound in the Laibin area, South China. *Australian Journal of Earth Sciences*, 56(6): 745–763
- Clapham M E, Renne P R. 2019. Flood basalts and mass extinctions. *Annual Review of Earth and Planetary Sciences*, 47: 275–303
- Day M O, Ramezani J, Bowring S A, Sadler P M, Erwin D H, Abdala F, Rubidge B S. 2015. When and how did the terrestrial mid-Permian mass extinction occur? Evidence from the tetrapod record of the Karoo Basin, South Africa. *Proceedings Biological Sciences*, 282(1811): 20150834
- Day M O, Benson R B J, Kammerer C F, Rubidge B S. 2018. Evolutionary rates of mid-Permian tetrapods from South Africa and the role of temporal resolution in turnover reconstruction. *Paleobiology*, 44(3): 347–367
- Ernst R E, Youbi N. 2017. How Large Igneous Provinces affect global climate, sometimes cause mass extinctions, and represent natural markers in the geological record. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 478: 30–52
- Ernst R E, Bond D P G, Zhang S H, Buchan K L, Grasby S E, Youbi N, Bilali H E, Bekker A, Doucet L S. 2021. Large igneous province record through time and implications for secular environmental changes and geological time - scale boundaries. *Large igneous provinces: A driver of global environmental and biotic changes*, 1–26
- Fan W M, Zhang C H, Wang Y J, Guo F, Peng T P. 2008. Geochronology and geochemistry of Permian basalts in western Guangxi Province, southwest China: Evidence for plume-lithosphere interaction. *Lithos*, 102(1–2): 218–236
- Fan W M, Wang Y J, Peng T P, Miao L C, Guo F. 2004. Ar-Ar and U-Pb geochronology of Late Paleozoic basalts in western Guangxi and its constraints on the eruption age of Emeishan basalt magmatism. *Chinese Science Bulletin*, 49(21): 2318–2327
- Fu J N, Pirajno F, Yang F, Shivute E, Sun Y Z, Ai N, Qiu K F. 2021. Integration of zircon and apatite U–Pb geochronology and geochemical mapping of the Wude basalts (Emeishan large igneous province): A tool for a better understanding of the tectonothermal and geodynamic evolution of the Emeishan LIP. *Geoscience Frontiers*, 12(2): 573–585
- Grasby S E, Beauchamp B, Bond D P, Wignall P B, Sanei H. 2016. Mercury anomalies associated with three extinction events (Capitanian Crisis, Latest Permian Extinction and the Smithian/Spathian Extinction) in NW Pangea. *Geological Magazine*, 153(2): 285–297
- Grasby S E, Liu X J, Yin R S, Ernst R E, Chen Z H. 2020. Toxic mercury pulses into Late Permian terrestrial and marine environments. *Geology*, 48(8): 830–833
- He B, Xu Y G, Chung S L, Xiao L, Wang Y M. 2003. Sedimentary evidence for a rapid, kilometer-scale crustal doming prior to the eruption of the Emeishan flood basalts. *Earth and Planetary Science Letters*, 213(3–4): 391–405
- He B, Xu Y G, Huang X L, Luo Z Y, Shi Y R, Yang Q J, Yu S Y. 2007. Age and duration of the Emeishan flood volcanism, SW China: Geochemistry and SHRIMP zircon U–Pb dating of silicic ignimbrites, post-volcanic Xuanwei formation and clay tuff at the Chaotian section. *Earth and Planetary Science Letters*, 255(3–4): 306–323
- 何冰辉. 2016. 关于峨眉山大火成岩省一些问题的研究现状. *地球科学进展*, 31(1): 23–42 [He B H. 2016. Research progress on some issues on the Emeishan large igneous province. *Advances in Earth Science*, 31(1): 23–42 (in Chinese with English abstract)]
- Hounsflow M W, Balabanov Y P. 2018. A geomagnetic polarity timescale for the Permian, calibrated to stage boundaries. *Geological Society, London, Special Publications*, 450(1): 61–103
- Huang H, Cawood P A, Hou M C, Ni S J, Yang J H, Du Y S, Wen H G. 2018. Provenance of Late Permian volcanic ash beds in South China: Implications for the age of Emeishan volcanism and its linkage to

- climate cooling. *Lithos*, 314: 293–306
- Huang H, Hou M C, Qing H R, Zhou L, Yang J H, Du Y S, Tian J C, Ni S J, Xiong F H. 2019. The contribution of the Emeishan large igneous province to the strontium isotope evolution of the Capitanian seawater. *International Geology Review*, 61(15): 1927–1939
- Huang H, Huyskens M H, Yin Q Z, Cawood P A, Hou M C, Yang J H, Xiong F H, Du Y S, Yang C C. 2022. *Geology*, 50(9): 1083–1087
- Huang H, Deng C Z, Grasby S E, Cawood P A, Hou M C, Yang C C, Feng M S, Xiong F H, Zhong H T, Yin R S. 2024. Mercury evidence of Emeishan volcanism driving the mid-Capitanian (Middle Permian) extinction. *Geological Society of America Bulletin*
- Huang Y G, Chen Z Q, Wignall P B, Grasby S E, Zhao L S, Wang X D, Kaiho K. 2019. Biotic responses to volatile volcanism and environmental stresses over the Guadalupian-Lopingian (Permian) transition. *Geology*, 47(2): 175–178
- Isozaki Y, Yao J X, Ji Z S, Saitoh M, Kobayashi N, Sakai H. 2008. Rapid sea-level change in the late Guadalupian (Permian) on the Tethyan side of South China: Litho- and biostratigraphy of the Chaotian section in Sichuan. *Proceedings of the Japan Academy Series B, Physical and Biological Sciences*, 84(8): 344–353
- Jicha B R, Singer B S, Li Y J. 2019. Intercalibration of $^{40}\text{Ar}/^{39}\text{Ar}$ laboratories in China, the USA and Russia for Emeishan volcanism and the Guadalupian-Lopingian boundary. *National Science Review*, 6(4): 614–616
- Jin Y G, Zhang J, Shang Q H. 1994. Two phases of the end-Permian mass extinction. *Pangea: Global Environments and Resources Memoir*, (17): 813–822
- Kwon H, Kim M G, Lee Y I. 2019. Mercury evidence from the Sino-Korean block for Emeishan volcanism during the Capitanian mass extinction. *Geological Magazine*, 156(6): 1105–1110
- Kuang M Z, Yuan H F, Li W J, Zhang B L, Shen C, Xiao Q R, Zhang X H, Peng H L, Chen C, Li T J. 2024. Potential effects of the Emeishan large igneous province on Capitanian marine anoxia in the Upper Yangtze region. *Global and Planetary Change*, 242: 104579
- 李献华, 柳小明, 刘勇胜, 苏犁, 孙卫东, HUANG HuiQing, YI Keewook. 2015. LA-ICPMS锆石U-Pb定年的准确度: 多实验室对比分析. *中国科学: 地球科学*, 45(9): 1294–1303 [Li X H, Liu X M, Liu Y S, Su L, Sun W D, Huang H Q, Keewook Y. 2015. Accuracy of LA-ICPMS zircon U-Pb age determination: An inter-laboratory comparison. *Scientia Sinica (Terra)*, 45(9): 1294–1303]
- 李献华, 李扬, 李秋立, 吴黎光, 王浩, 杨传, 韦刚健, 张万峰. 2022. 同位素地质年代学新进展与发展趋势. *地质学报*, 96(1): 104–122 [Li X H, Li Y, Li Q L, Wu L G, Wang H, Yang C, Wei G J, Zhang W F. 2022. Progress and prospects of radiometric geochronology. *Acta Geologica Sinica*, 96(1): 104–122 (in Chinese with English abstract)]
- Li Y J, He H Y, Ivanov A V, Demonerova E I, Pan Y X, Deng C L, Zheng D W, Zhu R X. 2018. $^{40}\text{Ar}/^{39}\text{Ar}$ age of the onset of high-Ti phase of the Emeishan volcanism strengthens the link with the end-Guadalupian mass extinction. *International Geology Review*, 60(15): 1906–1917
- Ling K Y, Wen H J, Grasby S E, Zhao H N, Deng C Z, Yin R S. 2023. The Emeishan large igneous province eruption triggered coastal perturbations and the Capitanian mass extinction: Insights from mercury in Permian bauxite beds. *Chemical Geology*, 617: 121243
- Liu C Y, Pan Y X, Zhu R X. 2012. New paleomagnetic investigations of the Emeishan basalts in NE Yunnan, southwestern China: Constraints on eruption history. *Journal of Asian Earth Sciences*, 52: 88–97
- 刘宣威, 田亚铭, 姜福杰, 王鹏威, 张慧, 柳昊, 李飞. 2023. 扬子西北缘二叠纪瓜德鲁普统-乐平统界线识别及意义. *沉积学报*, 1–28 [Liu X W, Tian Y M, Jiang F J, Wang P W, Zhang H, Liu H, Li F. 2023. Identification and Significance of the Permian Guadalupian - Lopingian Series Boundary in the Northwestern Margin of the Yangtze Craton. in *Journal of Sedimentology*, 1–28]
- Lo C H, Chung S L, Lee T Y, Wu G Y. 2002. Age of the Emeishan flood magmatism and relations to Permian-Triassic boundary events. *Earth and Planetary Science Letters*, 198(3–4): 449–458
- Maruoka T, Isozaki Y. 2020. Sulfur and carbon isotopic systematics of Guadalupian-Lopingian (Permian) mid-Panthalassa: $\delta^{34}\text{S}$ and $\delta^{13}\text{C}$ profiles in accreted paleo-atoll carbonates in Japan. *Island Arc*, 29(1): e12362
- Ota A, Isozaki Y. 2006. Fusuline biotic turnover across the Guadalupian-Lopingian (Middle-Upper Permian) boundary in mid-oceanic carbonate buildups: Biostratigraphy of accreted limestone in Japan. *Journal of Asian Earth Sciences*, 26(3–4): 353–368
- Payne J L, Clapham M E. 2012. End-Permian mass extinction in the oceans: An ancient analog for the twenty-first century? *Annual Review of Earth and Planetary Sciences*, 40(1): 89–111
- Pham T T, Shellnutt J G, Tran T A, Denysyn S W, Iizuka Y. 2022. Petrogenesis of silicic rocks from the Phan Si Pan-Tu Le region of the Emeishan large igneous province, northwestern Vietnam. *Geological Society of London Special Publications*, 518(1): 227–254
- Qiu Z, Wang Q C, Zou C N, Yan D T, Wei H Y. 2014. Transgressive-regressive sequences on the slope of an isolated carbonate platform (Middle-Late Permian, Laibin, South China). *Facies*, 60(1): 327–345
- Rampino M R, Shen S Z. 2019. The end-Guadalupian (259.8 Ma) biodiversity crisis: The sixth major mass extinction? *Historical Biology*, 33(5): 716–722
- Sahney S, Benton M J. 2008. Recovery from the most profound mass extinction of all time. *Proceedings Biological Sciences*, 275(1636): 759–765
- Saitoh M, Ueno Y, Isozaki Y, Nishizawa M, Shozugawa K, Kawamura T, Yao J X, Ji Z S, Ken T K, Yoshida N, Matsuo M. 2014. Isotopic evidence for water-column denitrification and sulfate reduction at the end-Guadalupian (Middle Permian). *Global and Planetary Change*, 123: 110–120
- Schoene B, Eddy M P, Samperton K M, Brenhin Keller C, Keller G, Adatte T, Khadri S F R. 2019. U-Pb constraints on pulsed eruption of the Deccan Traps across the end-Cretaceous mass extinction. *Science*, 363(6429): 862–866
- Sepkoski J J Jr. 1996. Patterns of Phanerozoic extinction: a perspective from global data bases. In: *Global Events and Event Stratigraphy in the Phanerozoic*. Berlin, Heidelberg: Springer Berlin Heidelberg: 35–51
- Shen S Z, Shi G R. 1996. Diversity and extinction patterns of Permian Brachiopoda of South China. *Historical Biology*, 12(2): 93–110
- Shen S Z, Shi G R. 2009. Latest Guadalupian brachiopods from the Guadalupian/Lopingian boundary GSSP section at Penglaitan in Laibin,

- Guangxi, South China and implications for the timing of the pre-Lopingian crisis. *Palaeoworld*, 18(2-3): 152-161
- 沈树忠, 张鹏飞, 王文倩, 王向东, 樊隽轩, 陈吉涛, 王博, 曹剑, 杨石岭, 张华, 李高军, 邓涛, 李献华, 陈骏. 2024. 深时重大生物和气候事件与全球变化: 进展与挑战. *科学通报*, 69(2): 268-285 [Shen S Z, Zhang F F, Wang W Q, Wang X D, Fan X F, Chen J T, Wang B, Cao J, Yang S L, Zhang H, Li G J, Deng T, Li X H, Chen J. 2024. Deep-time major biological and climatic events versus global changes: Progresses and challenges. *Chinese Science Bulletin*, 69(2): 268-285 (in Chinese with English abstract)]
- 沈树忠, 张华, 张以春, 袁东勋, 陈波, 何卫红, 牟林, 陈军, 吴琼, 曹长群, 王玥, 王向东. 2018. 中国二叠纪综合地层和时间框架. *中国科学: 地球科学*, 49(1): 160-193 [Shen S Z, Zhang H, Zhang Y C, Yuan D X, Chen B, He W H, Mou L, Chen J, Wu Q, Cao C Q, Wang Y, Wang X D. 2018. Permian integrative stratigraphy and timescale of China: *Earth Science*, 49 (1): 160-193]
- Shen S Z, Crowley J L, Wang Y, Bowring S A, Erwin D H, Sadler P M, Cao C Q, Rothman D H, Henderson C M, Ramezani J, Zhang H, Shen Y N, Wang X D, Wang W, Mu L, Li W Z, Tang Y G, Liu X L, Liu L J, Zeng Y, Jiang Y F, Jin Y G. 2011. Calibrating the end-Permian mass extinction. *Science*, 334(6061): 1367-1372
- Shen S Z, Zhang H, Zhang Y C, Yuan D X, Chen B, He W H, Mu L, Lin W, Wang W Q, Chen J, Wu Q, Cao C Q, Wang Y, Wang X D. 2019. Permian integrative stratigraphy and timescale of China. *Science China Earth Sciences*, 62(1): 154-188
- Shellnutt J G. 2014. The Emeishan large igneous province: A synthesis. *Geoscience Frontiers*, 5(3): 369-394
- Shellnutt J G, Denyszyn S W, Mundil R. 2012. Precise age determination of mafic and felsic intrusive rocks from the Permian Emeishan large igneous province (SW China). *Gondwana Research*, 22(1): 118-126
- Shellnutt J G, Pham T T, Denyszyn S W, Yeh M W, Tran T A. 2020. Magmatic duration of the Emeishan large igneous province: Insight from northern Vietnam. *Geology*, 48(5): 457-461
- Song H Y, Algeo T J, Song H J, Tong J N, Wignall P B, Bond D P G, Zheng W, Chen X M, Romaniello S J, Wei H Y, Anbar A D. 2023. Global oceanic anoxia linked with the Capitanian (Middle Permian) marine mass extinction. *Earth and Planetary Science Letters*, 610: 118128
- Sun Y D, Lai X L, Wignall P B, Widdowson M, Ali J R, Jiang H S, Wang W, Yan C B, Bond D P G, Vêdrine S. 2010. Dating the onset and nature of the Middle Permian Emeishan large igneous province eruptions in SW China using conodont biostratigraphy and its bearing on mantle plume uplift models. *Lithos*, 119(1-2): 20-33
- Stanley S M, Yang X. 1994. A double mass extinction at the end of the Paleozoic era. *Science*, 266(5189): 1340-1344
- Thomas D N, Rolph T C, Shaw J, Gonzalez de Sherwood S, Zhuang Z. 1998. Palaeointensity studies of a Late Permian lava succession from Guizhou Province, South China: Implications for post-Kiaman dipole field behaviour. *Geophysical Journal International*, 134(3): 856-866
- 童金南. 2021. 古生物学(第二版). 北京: 高等教育出版社 [Tong J N. 2021. *Paleontology* (Second Edition). Beijing: Higher Education Press (in Chinese)]
- Usuki T, Lan C Y, Tran T H, Pham T D, Wang K L, Shellnutt J G, Chung S L. 2015. Zircon U-Pb ages and Hf isotopic compositions of alkaline silicic magmatic rocks in the Phan Si Pan-Tu Le region, northern Vietnam: Identification of a displaced western extension of the Emeishan Large Igneous Province. *Journal of Asian Earth Sciences*, 97: 102-124
- Villier L, Korn D. 2004. Morphological disparity of ammonoids and the mark of Permian mass extinctions. *Science*, 306(5694): 264-266
- Wang C Y, Zhou M F, Sun Y L, Arndt N T. 2012. Differentiation, crustal contamination and emplacement of magmas in the formation of the Nantianwan mafic intrusion of the ~260Ma Emeishan large igneous province, SW China. *Contributions to Mineralogy and Petrology*, 164(2): 281-301
- Wang W Q, Garbelli C, Zhang F F, Zheng Q F, Zhang Y C, Yuan D X, Shi Y K, Chen B, Shen S Z. 2020. A high-resolution Middle to Late Permian paleotemperature curve reconstructed using oxygen isotopes of well-preserved brachiopod shells. *Earth and Planetary Science Letters*, 540: 116245
- Wang X D, Sugiyama T. 2000. Diversity and extinction patterns of Permian coral faunas of China. *Lethaia*, 33(4): 285-294
- Wignall P B, Sun Y D, Bond D P G, Izon G, Newton R J, Vêdrine S, Widdowson M, Ali J R, Lai X L, Jiang H S, Cope H, Bottrell S H. 2009. Volcanism, mass extinction, and carbon isotope fluctuations in the Middle Permian of China. *Science*, 324(5931): 1179-1182
- Wei H Y, Wei X M, Qiu Z, Song H Y, Shi G. 2016. Redox conditions across the G-L boundary in South China: Evidence from pyrite morphology and sulfur isotopic compositions. *Chemical Geology*, 440: 1-14
- 韦雪梅, 韦恒叶, 邱振. 2016. 瓜德鲁普末期生物灭绝是由峨眉山大火成岩省(LIP)引起的吗? *沉积学报*, 34(3): 436-451 [Wei X M, Wei H Y, Qiu Z. 2016. Was the end-guadalupian mass extinction caused by the Emeishan LIP eruption? *Acta Sedimentologica Sinica*, 34(3): 436-451 (in Chinese with English abstract)]
- Wu Q, Ramezani J, Zhang H, Yuan D X, Erwin D H, Henderson C M, Lambert L L, Zhang Y C, Shen S Z. 2020. High-precision U-Pb zircon age constraints on the Guadalupian in West Texas, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 548: 109668
- Wu Q, Zhang H, Ramezani J, Zhang F F, Erwin D H, Feng Z, Shao L Y, Cai Y F, Zhang S H, Xu Y G, Shen S Z. 2024. The terrestrial end-Permian mass extinction in the paleotropics postdates the marine extinction. *Science Advances*, 10(5): eadi7284
- Xu J, Xia X P, Lai C K, Zhou M L, Ma P F. 2019. First identification of Late Permian Nb-enriched basalts in Ailaoshan Region (SW Yunnan, China): Contribution from Emeishan plume to subduction of eastern paleotethys. *Geophysical Research Letters*, 46(5): 2511-2523
- Xu Y, Zheng L, Yang Z. 2022. Rapid eruption of the Emeishan continental flood basalts: New paleomagnetic and geochronologic constraints. *Geological Society of America Bulletin*, (7/8): 134
- Xu Y G, Chung S L, Jahn B M, Wu G Y. 2001. Petrologic and geochemical constraints on the petrogenesis of Permian-Triassic Emeishan flood basalts in southwestern China. *Lithos*, 58(3-4): 145-168
- Xu Y C, Zheng L D, Yang Z Y, Tong Y B, Wang B, Yuan W, Jing X Q. 2021. Rapid eruption of the Emeishan continental flood basalts: New paleomagnetic and geochronologic constraints. *GSA Bulletin*
- Xu Y G, He B, Chung S L, Menzies M A, Frey F A. 2004. Geologic,

- geochemical, and geophysical consequences of plume involvement in the Emeishan flood-basalt province. *Geology*, 32(10): 917–920
- Xu Y G, Chung S L, Shao H, He B. 2010. Silicic magmas from the Emeishan large igneous province, Southwest China: Petrogenesis and their link with the end-Guadalupian biological crisis. *Lithos*, 119(1–2): 47–60
- Yan D T, Zhang L Q, Qiu Z. 2013. Carbon and sulfur isotopic fluctuations associated with the end-Guadalupian mass extinction in South China. *Gondwana Research*, 24(3–4): 1276–1282
- Yan H, Pi D H, Xu L G, Sun K. 2023. The Perturbation of the Guadalupian Marine Environment Triggered by Early-Stage Eruption of the Emeishan Large Igneous Province: Rare Earth Element and Sr-Nd Isotope Evidence from Zunyi Manganese Deposit, South China. *Minerals*, 13(7): 965
- 杨晨晨, 黄虎, 邓昌州. 2022. 黔南马坡脚上二叠统吴家坪组凝灰岩成因及其地质意义. *矿物岩石地球化学通报*, 41(2): 397–413 [Yang C C, Huang H, Deng C Z. 2022. The origin and geologic significance of the tuff within the upper Permian wuchiaping formation at mapojiao in the southern Guizhou, China. *Bulletin of Mineralogy, Petrology and Geochemistry*, 41(2): 397–413 (in Chinese with English abstract)]
- Yang J H, Cawood P A, Du Y S. 2015. Voluminous silicic eruptions during Late Permian Emeishan igneous province and link to climate cooling. *Earth and Planetary Science Letters*, 432: 166–175
- Yang J H, Cawood P A, Du Y S, Condon D J, Yan J X, Liu J Z, Huang Y, Yuan D X. 2018. Early Wuchiapingian cooling linked to Emeishan basaltic weathering? *Earth and Planetary Science Letters*, 492: 102–111
- Zhang G J, Zhang X L, Li D D, Farquhar J, Shen S Z, Chen X Y, Shen Y N. 2015. Widespread shoaling of sulfidic waters linked to the end-Guadalupian (Permian) mass extinction. *Geology*, 43(12): 1091–1094
- 张招崇, 王福生, 郝艳丽. 2005. 峨眉山大火成岩省中的苦橄岩: 地幔柱活动证据. *矿物岩石地球化学通报*, 24(1): 17–22 [Zhang Z C, Wang F S, Hao Y L. 2005. Picrites from the Emeishan large igneous province: Evidence for the mantle plume activity. *Bulletin of Mineralogy Petrology and Geochemistry*, 24(1): 17–22 (in Chinese with English abstract)]
- 张桂洁. 2016. 二叠纪两次生物大灭绝期间海洋化学条件的变化(博士学位论文). 合肥: 中国科学技术大学. [Zhang G J. 2016. The ocean chemistry changes associated with two mass extinction events in Permian (Doctoral Dissertation). Hefei: University of Science and Technology of China (in Chinese with English abstract)]
- Zheng L D, Yang Z Y, Tong Y B, Yuan W. 2010. Magnetostratigraphic constraints on two-stage eruptions of the Emeishan continental flood basalts. *Geochemistry, Geophysics, Geosystems*, 11(12): Q12014
- 郑连弟. 2012. 峨眉山大火成岩省的磁性年代学研究——以宾川和盐源玄武岩区为例 (博士学位论文). 南京: 南京大学 [Zheng L D. 2012. Magnetic Chronology Study of Emeishan Large Igneous Province (Doctoral Dissertation). Nanjing: Nanjing University (in Chinese with English abstract)]
- 郑连弟. 2012. 峨眉山大火成岩省的磁性年代学研究: 以宾川和盐源玄武岩区为例(博士学位论文). 南京: 南京大学. [Zheng L D. 2012. Magnetotratigraphic dating on the Emeishan Large Igneous province, the results from the Binchuan and Yanyuan areas (Doctoral Dissertation). Nanjing: Nanjing University (in Chinese with English abstract)]
- Zhong Y T, Mundil R, Chen J, Yuan D X, Denysyn S W, Jost A B, Payne J L, He B, Shen S Z, Xu Y G. 2020. Geochemical, biostratigraphic, and high-resolution geochronological constraints on the waning stage of Emeishan Large Igneous Province. *Geological Society of America Bulletin*, 132(9–10): 1969–1986
- Zhong Y T, He B, Mundil R, Xu Y G. 2014. CA-TIMS zircon U-Pb dating of felsic ignimbrite from the Binchuan section: Implications for the termination age of Emeishan large igneous province. *Lithos*, 204: 14–19
- Zhou M F, Malpas J, Song X Y, Robinson P T, Sun M, Kennedy A K, Leshner C M, Keays R R. 2002. A temporal link between the Emeishan large igneous province (SW China) and the end-Guadalupian mass extinction. *Earth and Planetary Science Letters*, 196(3–4): 113–122
- Zhu B, Guo Z J, Zhang S N, Ye N, Lu Z Y, Huang B W. 2021. Low-Ti gabbroic pluton in Dali, SW China: New evidence for back-arc lithospheric melting inducing early-stage magmatism of the Emeishan large igneous province. *Journal of the Geological Society*, 178(6): jgs2020–224
- Zhu J, Zhang Z C, Santosh M, Tan S C, Jin Z L. 2021. Submarine basaltic eruptions across the Guadalupian-Lopingian transition in the Emeishan large igneous province: Implication for end-Guadalupian extinction of marine biota. *Gondwana Research*, 92: 228–238
- Zhu J, Zhang Z C, Reichow M K, Li H B, Cai W C, Pan R H. 2018. Weak vertical surface movement caused by the ascent of the Emeishan mantle anomaly. *Journal of Geophysical Research: Solid Earth*, 123(2): 1018–1034

(本文责任编辑: 谭亲平, 李溪遥; 英文审校: 张兴春)