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基于地质大数据的晚三叠世–早侏罗世全球古野火事件分布及控制因素分析

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摘 要: 陆地野火是全球生态系统演化的重要驱动因素之一,研究关键地质历史时期的古野火事件及其控制机制,有助于深入揭示古气候、古环境演变与古野火活动之间的内在联系.基于木炭、惰质组和热解多环芳烃共计268条野火记录,系统分析了晚三叠世至早侏罗世(237~174.7 Ma)全球古野火空间分布及背后的控制因素.研究发现,晚三叠世卡尼期至诺利期–瑞替期边界古野火集中分布于北半球中低纬度热带、暖温带区域,仅卡尼期古野火在南半球暖温带少量分布;瑞替期至瑞替期–赫塘期边界(T-J边界),古野火在北半球中纬度多气候带呈均匀分布;早侏罗世野火则集中分布于北半球中纬度暖温带与北热带区域.晚三叠世至早侏罗世全球古野火事件的时空分布,受pCO_2、pO_2、植被和大型地质事件的共同影响.晚三叠世初期Wrangellia大火成岩省(LIP)活动促进大气pCO_2快速升高,叠加植被繁盛与高大气氧含量(pO_2),共同促使卡尼期野火高频发生;早诺利期pCO_2达峰值后持续下降,伴随pO_2降低共同抑制了诺利期野火活动;后续Angayucham LIP与中大西洋大火成岩省(CAMP)火山活动依次促进pCO_2跨T-J边界长时间持续回升,该阶段植被群落结构趋于稳定,促使诺利期–瑞替期边界、瑞替期、瑞替期–赫塘期边界及赫塘期野火频率呈升高趋势.全球多个T-J典型剖面碳同位素负偏移对主要受CAMP驱动的瑞替期–赫塘期边界的高频野火事件发生响应;辛涅缪尔期受pO_2持续下降与气候转冷影响,野火频率骤降;早侏罗世中晚期pCO_2整体处于低位,仅托尔期pO_2回升使得野火数量略高于普林斯巴奇期,但野火频率则无明显变化.

关键词: 晚三叠世–早侏罗世;古野火事件;古气候;中大西洋大火成岩省(CAMP);地质事件;古气候学.

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Distribution of Global Paleowildfire Events and Controlling Factors from Late Triassic to Early Jurassic Based on Geological Big Data

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Abstract: Terrestrial wildfires are among the important driving forces in the evolution of global ecosystems. Studying paleowildfire events and their control mechanisms during key periods in geological history helps reveal the intrinsic connections between climatic

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and environmental evolution and wildfire activity. A total of 268 paleowildfire records reported worldwide, including records of charcoal, inertinite, and pyrogenic polycyclic aromatic hydrocarbons, were analyzed for the interval from Late Triassic to Early Jurassic (237-174.7 Ma). The study reveals that the spatial distribution of paleowildfires from the Carnian of the Late Triassic to the Norian-Rhaetian boundary was concentrated in tropical and warm-temperate zones at low to mid-latitudes in the Northern Hemisphere, with only a small number of Carnian paleowildfires distributed in the warm-temperate zone of the Southern Hemisphere. From the Rhaetian to the Rhaetian-Hettangian boundary (the Triassic-Jurassic /T-J boundary), paleowildfires were uniformly distributed across multiple climatic belts at mid-latitudes in the Northern Hemisphere. Wildfires in the Early Jurassic were concentrated in the warm-temperate and northern tropical zones at mid-latitudes in the Northern Hemisphere. Global paleowildfire activity from the Late Triassic to the Early Jurassic was controlled by combined effects of pCO_2 (10^{-6}; atmospheric CO_2 concentration) and pO_2 (vol%; atmospheric O_2 volume fraction), vegetation change, and major geological events. The volcanic activity of the Wrangellia Large Igneous Province (LIP) in the Early Late Triassic promoted a rapid rise in pCO_2. This rise, together with flourishing vegetation and high pO_2, collectively drove the high frequency of wildfires during the Carnian. After pCO_2 peaked in the Early Norian, it continued to decline, and this decline, together with the decrease in pO_2, suppressed wildfire activity during the Norian. Subsequently, volcanic activity associated with the Angayucham LIP and the Central Atlantic Magmatic Province (CAMP) sequentially promoted the long-term recovery in pCO_2 across Triassic-Jurassic (T-J) boundary. During this period, the structure of vegetation communities remained relatively stable, which contributed to an increase in wildfire frequency at the Norian-Rhaetian boundary, during the Rhaetian, at the Rhaetian-Hettangian boundary, and during the Hettangian. Negative carbon-isotope excursions recorded in multiple representative T-J boundary sections worldwide are interpreted as responses to the high-frequency wildfire events at the Rhaetian-Hettangian boundary, which were mainly driven by CAMP volcanism. With the continued decline in pO_2 and climatic cooling during the Sinemurian, wildfire frequency dropped sharply. In the middle and late stages of the Early Jurassic, pCO_2 generally remained at a low level. Only the recovery of pO_2 during the Toarcian resulted in a slightly higher number of wildfires than in the Pliensbachian, while wildfire frequency remained almost unchanged.

Key words: Late Triassic-Early Jurassic; wildfire; paleoclimate; Central Atlantic Magmatic Province (CAMP); geological event; paleoclimatology.

0 引言

古野火是影响地球生态系统变迁的重要因素，在全球碳循环、气候变化以及陆地植物演化过程中发挥着关键的调节作用(Finkelstein *et al.*, 2005; Bowman *et al.*, 2009; 占长林等, 2011; Shao *et al.*, 2024).现有研究表明，古野火事件最早出现于志留纪陆地生态系统形成初期，Glasspool and Gastaldo(2022)在英国志留系地层中发现了距今约430 Ma的木炭化石，证实野火自陆地植被出现以来就深度参与了陆地生态系统的塑造：通过调控古大气氧含量、促进养分循环，推动了陆地植被从低等生物结皮向复杂维管植物群落的长期演化(Edwards and Feehan, 1980; Belcher *et al.*, 2010b; Kump, 2014; Wellman and Ball, 2021).晚古生代古野火活动与大气氧含量波动高度耦合，直接影响了陆地植物的辐射演化进程(Scott and Glasspool, 2006; Glasspool *et al.*, 2015)；二叠纪末生物大灭绝、白垩纪大洋缺氧事件等极端气候事件期，均观测到野火频率的显著突变，显示古野火是深时气候与生态系统变化的敏感响应指标(Jasper *et al.*, 2008, 2013; Kauffmann *et al.*, 2016; Lü *et al.*, 2024).当前全球变暖背景下，野火的频率与强度呈显著上升趋势(Running, 2006; Jones *et al.*, 2020)，加强对深时古野火-气候-生态系统的耦合机制的认识，可为未来全球气候变化提供重要的地质类比.

晚三叠世-早侏罗世是地球系统演化的关键转折窗口，该时段既包含了中大西洋火成岩省(CAMP)的巨量喷发(Blackburn *et al.*, 2013; Marzoli *et al.*, 2019; Davies *et al.*, 2021)、古大气CO_2浓度升高、全球快速升温和三叠纪末全球生物大灭绝事件(～201.4 Ma; Davies *et al.*, 2017; 侯海海等, 2023)；也伴随了陆地植被以裸子植物为绝对主导(Li *et al.*, 2018)向被子植物祖先类群早期分化过渡(Li *et al.*, 2019; Wang *et al.*, 2026).该地质历史阶段具有多重影响因素耦合的特点，研究该时期的古野火活动演变有助于深化对气候-植被-野火系统的重新认识.同时该时期的古野火和古气候研究也受到全球学者的高度关注，已发表学术论文中出现的高频词汇包括木炭、惰质组、野火、多环芳烃、大

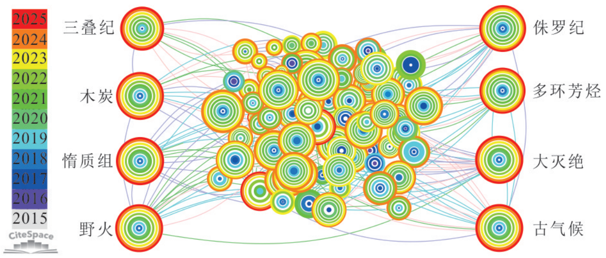

图1　三叠纪-侏罗纪古野火与古气候相关聚集图谱与发文时间演变图

Fig.1　Correlation map and temporal trend of publications on Triassic - Jurassic paleowildfire and paleoclimate

灭绝、古气候等(图1).

目前晚三叠世-早侏罗世的古野火研究已取得多方面进展：①全球范围的记录证实晚三叠世野火活动整体频繁，北美、南美、欧洲、南极等区域在卡尼期，诺利期与瑞替期地层中分别发现可靠的木炭与惰质组记录(Jones *et al.*, 2002; Zeigler *et al.*, 2005; Colombi and Parrish, 2008; Uhl *et al.*, 2008; Kumar *et al.*, 2011; Uhl and Montenari, 2011)，这一特征与该时期大气氧含量回升、裸子植物(松柏类、苏铁类)大范围扩张提供充足燃料的背景有关(Looy, 2007; Belcher *et al.*, 2010b; Abu Hamad *et al.*, 2012)；②三叠-侏罗纪界线(TJB)的局部剖面研究显示，TJB界线处野火频率上升与CAMP喷发导致的 pCO_2 升高、闪电频率增加、植被可燃性提升相关(Belcher *et al.*, 2010a; Zhang *et al.*, 2022)；③早侏罗世野火记录存在显著的时空差异性，被认为与大气氧含量波动、干湿气候交替、裸子植物群落分布共同调控有关(Cai *et al.*, 2021a; Du *et al.*, 2024; Sha *et al.*, 2024).

但当前研究仍存在不足：①现有记录多聚焦单个剖面或TJB前后的短时间窗口(Jones *et al.*, 2002; Zeigler *et al.*, 2005; Belcher *et al.*, 2010a; Alipour *et al.*, 2021; Sha *et al.*, 2024)，对涵盖晚三叠世-早侏罗世全球古野火时空规律及背后主控因素仍不明确.②虽然前人对T-J边界之后的侏罗纪全球与区域野火事件研究较为充分(Du *et al.*, 2024; Zhou *et al.*, 2024)，但缺乏对跨越整个晚三叠世-早侏罗世的全球尺度野火时空演化分析.仅基于单一或少量剖面的分析难以区分局地信号与全球规律，对已发表数据的简单统计也无法校正不同指标、不同沉积相带来的记录偏差，因此亟须采用地质大数据分析思路开展系统研究.

本研究区别于传统的数据库汇总分析，基于地质大数据方法重建全球晚三叠世-早侏罗世古野火活动序列：首先系统收集已发表的该时段木炭、惰质组与PAHs记录，通过标准化数据流程对不同指标的古野火类型进行统一校准.其次结合古地理重建模型，对不同板块的记录进行古经度、古纬度的时空转换，构建全球尺度的古野火数据集.最后整合古大气(pO_2、pCO_2)、植物群落组成等多源数据，关联大火成岩省喷发等重大地质事件，系统揭示晚三叠世-早侏罗世古野火的时空分异规律，探讨气候-植被-野火系统的协同演化关系.本研究结果不仅可深化对晚三叠世-早侏罗世气候演变及生物灭绝过程的认识，也可为预测未来全球气候变暖背景下的野火活动趋势提供深时地质依据.

1　材料与方法

地质历史时期的古野火记录主要来源于沉积地层中保存的不完全燃烧产物，包括宏观/微观木炭、煤中惰质组、热解多环芳烃(PAHs)三类核心证据，为研究深时野火活动提供了独特视角(Scott, 2000, 2010; Uhl *et al.*, 2012a; Glasspool *et al.*, 2015; Baker, 2022; Shao *et al.*, 2024; Sun, 2024).三类证据中，木炭因可保存植物原始解剖结构、燃烧温度等直接信息，是古野火识别的最可靠标志物(Scott, 2000; Scott and Glasspool, 2007; 张筱青等, 2016; 杨博等, 2022; 孙清泉等, 2024)，惰质组的显微结构与反射率特征(Glasspool and Scott, 2010; Xu *et al.*, 2020; Hou *et al.*, 2023; 侯海海等, 2025)和特定热解PAHs(如芘、苯并芘等)的富集(Nabbefeld *et al.*, 2010; Shen *et al.*, 2011a)，可进一步佐证古野火活动的存在(张瑞等, 2014; Xu *et al.*, 2020).

在全球范围内收集晚三叠世至早侏罗世全球古野火相关数据并构建了专门数据库，基于数据库统计和分析该时期古野火事件的时空变化特征.本次数据源主要包括两个方面：(1)对已有的相关数据进行整理分析，如Glasspool and Scott(2010)的显生宙惰质组数据库和Du *et al.*(2024)侏罗纪古野火记录的数据库.(2)增加并补充新的数据，数据搜集主要通过谷歌学术、中国知网和Web of Science等网络平台开展，所选关键词包括“三叠纪野火”、“晚三叠世-早侏罗世野火”、“木炭”、“惰质组”和“热解多环芳烃”等.该数据库检索收集时间截至2026年2月.

为了尽可能避免一次古野火发生时残留的不

同种类证据被误认为是由多次野火所引发，在同一地理位置的同一地层中，出现的多种野火证据（木炭，惰质组，热解多环芳烃）被归为一次野火事件或记录（Du *et al.*, 2024；吕大炜等，2025）.由于沉积物中的化石木炭被广泛认为是古野火的直接证据（Scott, 2000），对相同地理位置同一地层含有木炭或含有木炭且同时含有其他类野火证据的样品归为木炭类.惰质组的主要成分丝质体是由火焚形成，其性质稳定（Scott, 1989, 2010；Shao *et al.*, 2024），这里对不含木炭，但含有惰质组或含惰质组和多环芳烃的样品归为惰质组类.多环芳烃也被认为是燃烧事件存在的标志，如芘、苯并荧蒽、苯并芘、苯并苝和晕苯等（Nabbefeld *et al.*, 2010；Shen *et al.*, 2011a），对仅含有热解多环芳烃，不含木炭和惰质组的样品归为热解多环芳烃类.此外，为了展示晚三叠世-早侏罗世不同时间段古野火事件的空间分布情况，运用Gplates软件（版本2.4.0；可在www.gplates.org获取）进行古经纬度转化，并投点到Scotese（2016）编制的古地理图上.

在分析古野火事件发生控制因素过程中，参考了古大气pO_2水平（Mills *et al.*, 2023）、古大气pCO_2（Foster *et al.*, 2017）和植被多样性（Cleal and Cascales-Miñana, 2014）的相关研究.由于不同指标导致的pO_2重建结果存在显著差异，本研究采用了Mills *et al.*（2023）提出的氧重建方法，该方法整合了多个指标进行估算，有助于减少因个别指标引起的估算结果的变异性，提高代表性.pCO_2则采用Foster *et al.*（2017）通过Monte Carlo-LOESS方法整合多源数据得到的最优拟合曲线，其方法平衡了数据代表性与不确定性.其中，68%和95%置信区间分别用于表征CO_2浓度的主要变化区间（数据的核心波动范围）与极端边界（覆盖极端值和高不确定性区域），该最优拟合曲线在实际应用中具有良好的平滑特性、统计稳健性以及对长期趋势的有效识别能力.古气候带则采用Boucot *et al.*（2013）的划分方法，将晚三叠世划分为热带、北热带、暖温带与干旱带，早侏罗世划分为热带、北热带、暖温带、干旱带以及寒温带.

在数据收集和处理过程中，如出现大量处于两个地质时期边界的数据，会单独设立时间节点.本次研究将晚三叠世至早侏罗世共计划分为9个地质历史时间段（表1），单独设立时间节点的数据包括诺利期-瑞替期边界，瑞替期-赫塘期边界（即晚三叠世-早侏罗世边界）.

表1 本研究中使用的晚三叠世至早侏罗世9个地质历史时间段划分

Table 1 Division of nine geological time intervals from Late Triassic to Early Jurassic

时期	持续时间（Ma）	时间范围（Ma）
托尔期（Toarcian）	9.5	184.2～174.7
普林斯巴奇期（Pliensbachian）	8.7	192.9～184.2
辛涅缪尔期（Sinemurian）	6.6	199.5～192.9
赫塘期（Hettangian）	1.9	201.4～199.5
瑞替期-赫塘期边界	-	201.4
瑞替期（Rhaetian）	7.1	208.5～201.4
诺利期-瑞替期边界	-	208.5
诺利期（Norian）	18.5	227～208.5
卡尼期（Carnian）	10.0	237～227

2 结果

2.1 晚三叠世-早侏罗世古野火记录

本研究所收集分析的晚三叠世与早侏罗世全球古野火事件数据库共包含268条数据，其中晚三叠世145条记录，晚三叠世-早侏罗世边界31条记录，早侏罗世92条记录.依据不同古野火事件证据类型，古野火记录分别为153条惰质组数据（占57.1%）、88条木炭数据（占32.8%）以及27条热解多环芳烃数据（占10.1%）.7个时间段和两个时期边界中，惰质组证据均为主要数据源，占全部数据的29.0%～94.4%，平均为59.8%.木炭证据数量次之，占全部数据的5.6%～44.4%，平均为30.9%.热解多环芳烃证据最少，占全部数据的0～35.5%，平均为9.3%（图2），且数据的空间分布呈现出显著的南北半球与东西半球差异（图3）.

该数据库中，晚三叠世与早侏罗世古野火事件数据共记录在全球121个地层单元（或地层）中.其中255条古野火记录来自碎屑岩为主的岩石中，包括砂岩、粉砂岩、泥岩、页岩和煤，13条古野火证据记录在灰岩、泥灰岩中（见附表）.下面分别从不同时期与不同空间的角度对晚三叠世与早侏罗世古野火记录分布进行分析.

2.2 晚三叠世-早侏罗世不同时期古野火分布

晚三叠世-早侏罗世古野火记录数据库中，三类古火灾材料在不同地质时期呈不同特征（图2a）.晚三叠世阶段：整体以惰质组为核心主导组分，卡尼期惰质组占比达59.1%，为绝对优势；诺利期惰质

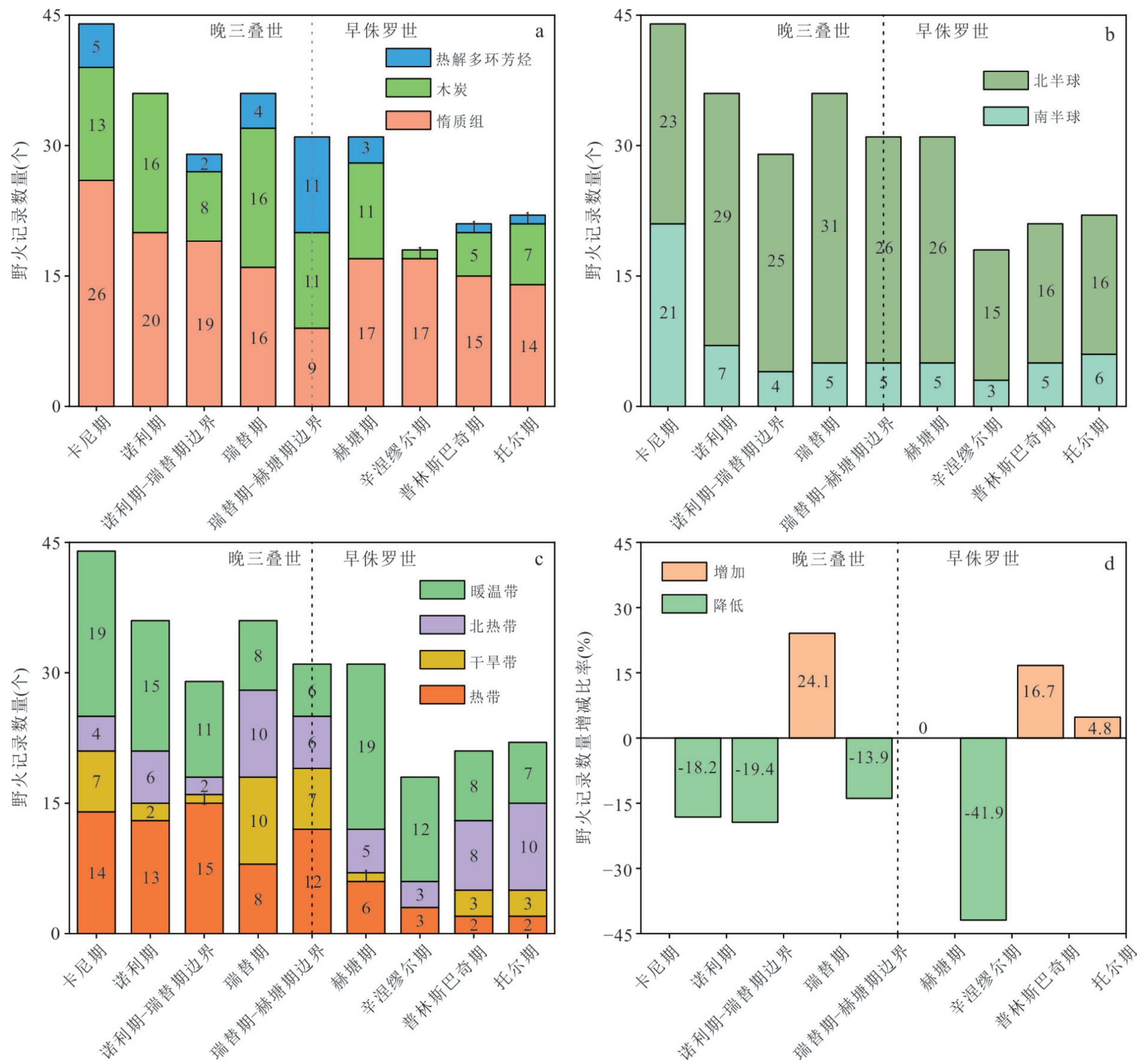

图 2　晚三叠世-早侏罗世不同时期全球古野火事件分布

Fig.2　Global distribution of Late Triassic - Early Jurassic paleowildfire events through different geological time

组略降至 55.6%，木炭占比提升至 44.4%，热解多环芳烃暂时消失；诺利期-瑞替期边界惰质组回升至 65.5% 重占主导，野火记录总数从 36 条降至 29 条；瑞替期惰质组与木炭占比均等（各 44.4%），热解多环芳烃占比回升至 11.1%.

三叠系-侏罗系界线（瑞替期-赫塘期边界，关键转折期）：惰质组骤降至 29.0%，木炭、热解多环芳烃占比均升至 35.5%，三类占比接近均衡，反映三叠纪末生物大灭绝背景下的野火事件频发，导致木炭、惰质组和多环芳烃生成同步激增，野火频率、强度发生显著突变.

早侏罗世阶段：组分逐步向晚三叠世常态回归，赫塘期惰质组回升至 54.8%，热解多环芳烃回落至 9.7%；辛涅缪尔期惰质组占比接近 100%，其余两类材料近乎消失，野火记录总量仅 17 条，为全时段最低；普林斯巴奇期、托尔期惰质组占比分别维持在 71.4%、63.6%，木炭、热解多环芳烃占比小幅回升，三类材料组分结构接近晚三叠世卡尼期（图 2a）.

7 个时间段与 2 个时期边界中，每个时期的古野火记录相较于前一个时期的增减比率变化与古野火数量变化总体趋势相似.晚三叠世古野火事件数量呈减-增-减上下波动的趋势，增减比率均在 25% 以内.早侏罗世的古野火记录数量则呈现先稳定后减少，之后缓慢增加的趋势，且增减比率大幅度波动，其中赫塘期至辛涅缪尔期出现大幅度降低，为 −41.9%，而辛涅缪尔期至普林斯巴奇期则呈现明显增长（图 2d）.

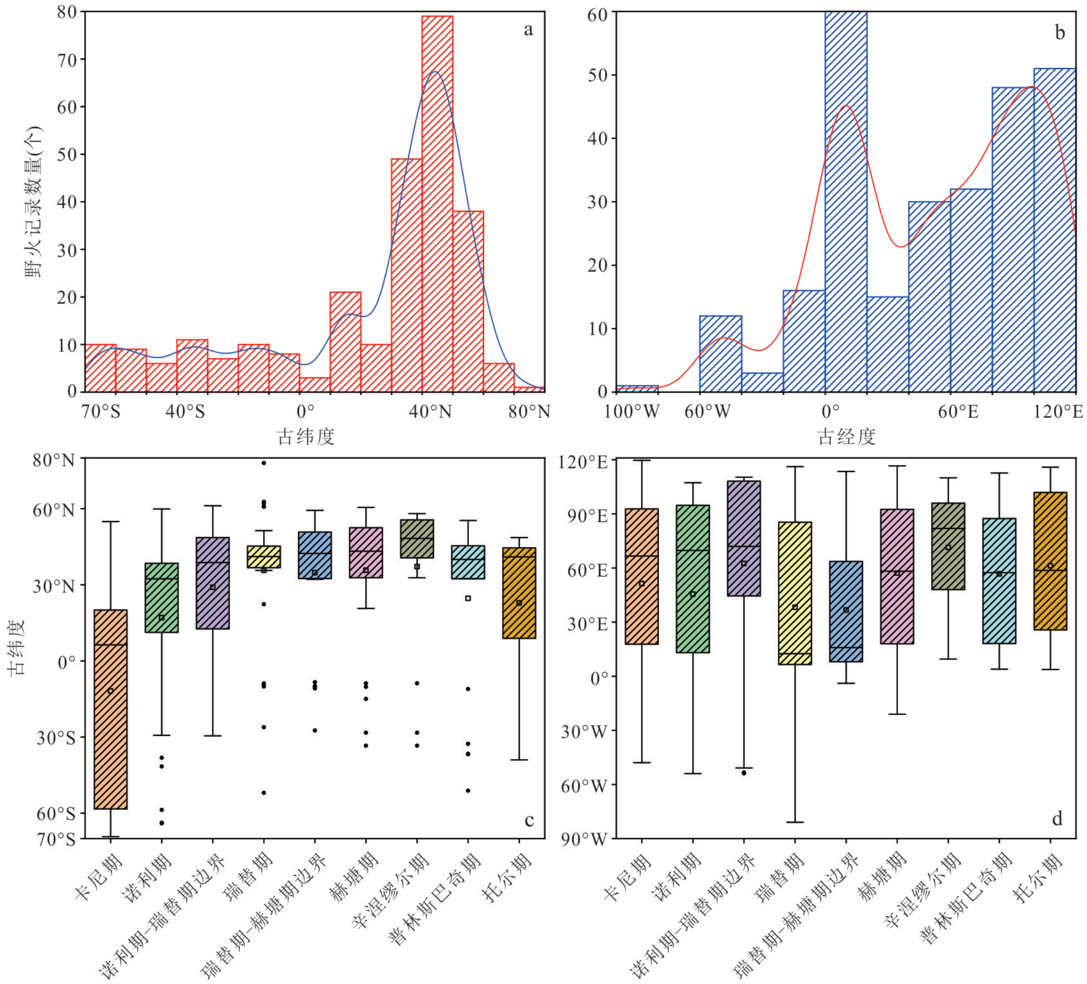

图3 晚三叠世-早侏罗世全球古野火事件的经纬度分布

Fig.3 Global distribution of Late Triassic - Early Jurassic paleowildfire events by latitude and longitude

2.3 晚三叠世-早侏罗世不同区域古野火分布

为分析不同地质历史时期古野火时空分布关系，将晚三叠世-早侏罗世古野火记录依据不同的时期划分投点到相应的古地理图中(图4～图6).对于不同半球分布而言，仅卡尼期古野火记录南北半球分布均匀，其余时间段北半球古野火事件的记录显著多于南半球(图2b).对于不同的古气候带而言，卡尼期至诺利期-瑞替期边界，古野火事件主要分布在暖温带与热带，二者平均占比80.8%，于北热带与干旱带分布较少，而瑞替期与瑞替期-赫塘期边界时期的古野火事件记录在暖温带、北热带、干旱带与热带四个气候带中呈均匀分布.整个早侏罗世期间，古野火事件主要分布在暖温带与北热带，二者平均占比78.3%，热带地区少量分布，干旱带地区零星分布，寒温带地区则没有古野火记录(图2c).对于不同纬度带而言，古野火事件遍布南北半球低纬度、中纬度与高纬度地区(70°S～80°N)，且集中分布在北半球中纬度热带、北热带地区(30°N～60°N).北半球低纬度与南半球中低纬度干旱带地区(60°S～30°N)少量分布，高纬度暖温带地区零星分布(图3a).7个时间段与2个时间边界中，卡尼期古野火记录主要分布在南半球中低纬度地区(0°～60°S)，其余时期古野火记录主要分布在北半球中低纬度地区(0°～60°N)，仅卡尼期、诺利期和瑞替期古野火事件在高纬度地区有零星分布(图3c).

从经度带划分来看，7个时间段与2个时间边界中，古野火事件主要发生在东半球(0°～120°E)，且在0°E～20°E地区古野火记录分布最多，从20°E向东至120°E地区，古野火记录数量呈逐渐增多趋势，而西半球0°～100°W地区古野火事件分布较少(图3b).晚三叠世与早侏罗世古野火记录主要集中分布在东半球0°～120°E范围内.晚三叠世各个时期，古野火记录在西半球(0°～90°W)均有少量分布，三叠纪-侏罗纪边界与早侏罗世赫塘期古野火事件在西

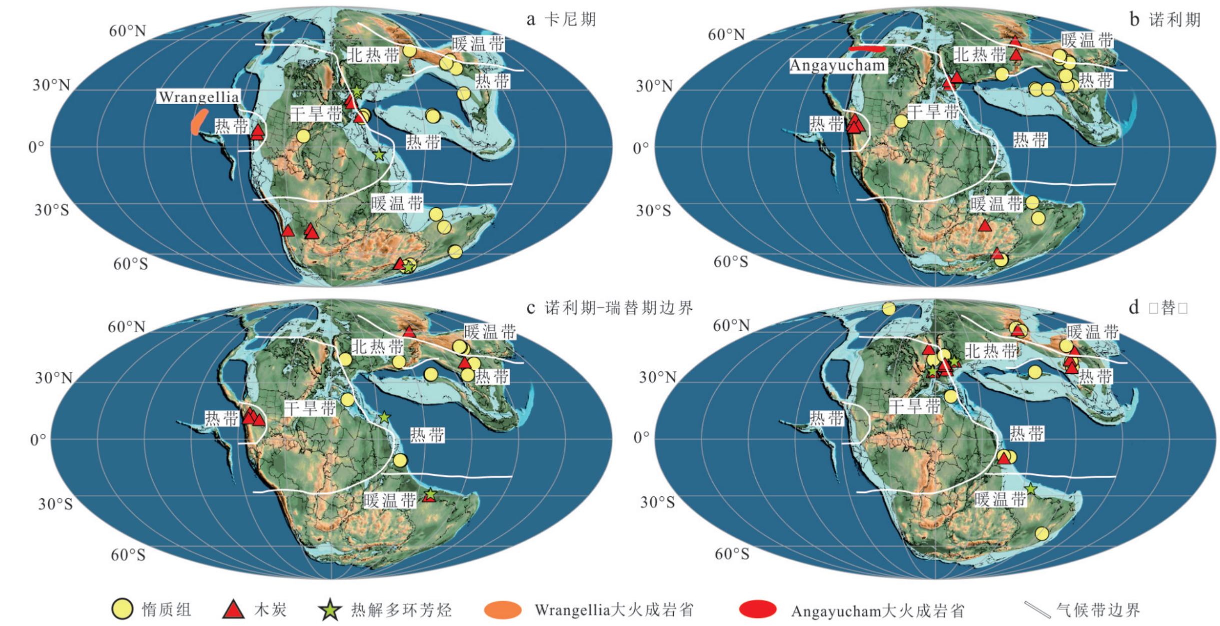

图 4　晚三叠世古野火事件古地理分布

Fig.4　Paleogeographic distribution of Late Triassic paleowildfire events

古气候带划分据 Boucot *et al.*（2013）；Wrangellia LIP 据 Dal Corso *et al.*（2020）；Angayucham LIP 据江海水和陈龚（2025）

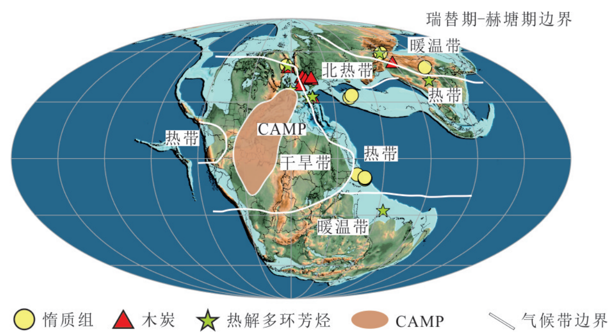

图 5　晚三叠世-早侏罗世边界古野火事件与不同区域古地理分布

Fig.5　Paleowildfire events and paleogeographic distribution across Late Triassic - Early Jurassic boundary

古气候带划分据 Boucot *et al.*（2013）；CAMP 范围据 Marzoli *et al.*（2011, 2017）

半球（0°～30°W）零星分布，辛涅缪尔期至托尔期古野火事件则全部分布在东半球（图 3d）.

3　讨论

3.1　古野火发生的控制因素概述

古野火发生的控制因素在不同时空尺度上有所不同. 在较小空间范围内，充足的氧气、燃料与较少的热量来源便足以促使零星的古野火发生；随着空间范围略微扩大，天气与地形分别影响了燃料中的水分与火势的蔓延方式，进而控制古野火的发生与范围，如山地坡度提供上升气流，促使火势更猛烈；随着空间尺度进一步扩大，易燃的植被类型往往使古野火的发生频率升高，温带季风气候相比更加潮湿的热带气候更容易着火，地势更高的地区相较低洼平坦地区更加干旱，火灾更易发生（Scott，2018；Bond，2019）. 为了更好地理解古野火的燃烧以及燃烧范围的众多控制因素，将其总结为火之三角形（图 7）.

在实际研究中可能更关注古野火如何被点燃，pO_2（助燃氧化）、燃料（可燃物供给）及点火源（触发机制）是其主要的三类影响因素（Scott，2000，2018；Glasspool *et al.*，2015；Bond，2019；Baker，2022；Du *et al.*，2024；吕大炜等，2024）. pO_2 作为燃烧反应的氧化剂，是维持古野火的基础条件（Scott，2018；Bond，2019）. 显生宙 pO_2 呈现显著波动，其浓度范围在 10%～35% 之间变化（韩德馨等，1996；Berner，2006；Belcher and McElwain，2008）. 燃烧实验表明，持续性燃烧需 $pO_2 \geq 16\%$，当 $pO_2 > 21\%$ 时野火发生概率显著提升，而 $pO_2 > 23\%$ 将导致野火事件普遍化（Cope and Chaloner，1980；Belcher *et al.*，2010b；Belcher，2013）. 此外，高氧环境还可以降低燃料引燃湿度的阈值，并延长燃烧持续时间（Diessel，2010；Watson and Lovelock，2013；Xu *et al.*，2020）.

燃料特性包括植被类型、生物量积累及湿度状

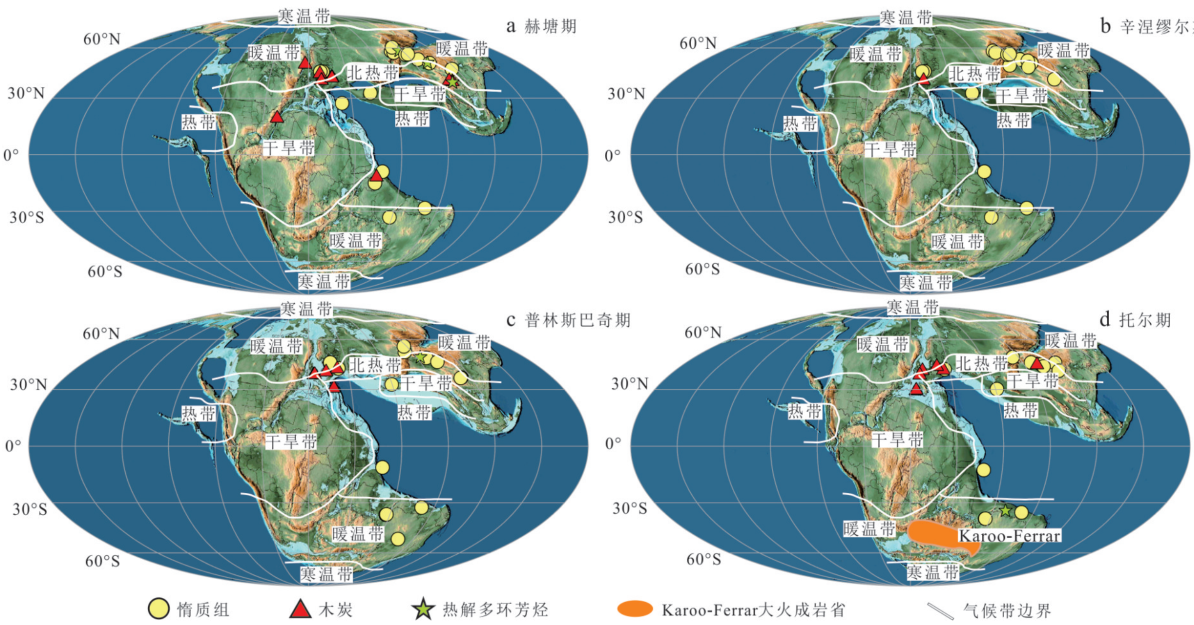

图6 早侏罗世古野火事件古地理分布

Fig.6 Paleogeographic distribution of Early Jurassic paleowildfire events

古气候带划分据 Boucot *et al.*(2013)；Karoo-Ferrar LIP 据 Ivanov *et al.* (2017)

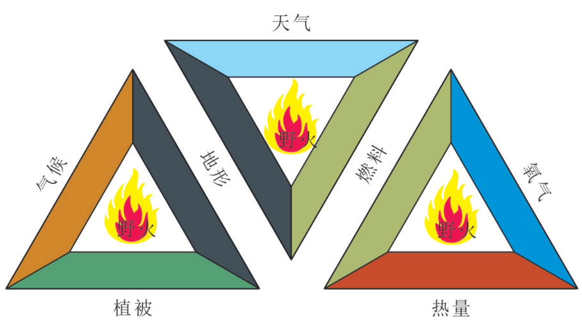

图7 野火发生的影响因素分析

Fig.7 Factors controlling wildfire occurrence

态，直接影响可燃物的燃烧效率与传播能力(Scott, 2018; Bond, 2019).地质记录显示，温暖湿润的气候条件支撑陆地维管植物快速扩散，大面积森林的形成为古野火活动规模跃升提供了物质基础(Shen *et al.*, 2011b;沈文杰等, 2012)，气候驱动下的植被演化促使燃料特性发生变化(如裸子植物向被子植物转变)，同时干旱化过程会降低燃料含水量，导致古野火频率上升，热解多环芳烃(PAHs)丰度异常升高(Collinson *et al.*, 2007; Denis *et al.*, 2017).此外，现代生态模型也进一步证实植被群落结构变化可使野火发生率产生2~3个数量级的差异(Baker, 2022).

点火源作为野火触发的关键因素，其时空分布直接影响古野火事件的发生频率(Scott, 2018; Bond, 2019).地质时期的自然点火机制包括火山活动、陨石撞击及闪电等(Bowman *et al.*, 2009; Scott, 2000)，其中闪电因其广泛性和持续性成为最主要的点火源(Glasspool *et al.*, 2010).同时，pCO_2升高会增强对流层水汽循环，提升雷暴频率与闪电密度(Price and Rind, 1994; Belcher *et al.*, 2010a; Denis *et al.*, 2017).雷击作为地质历史时期古野火的主要点火源，在潮湿的环境下更加多发(Cope and Chaloner, 1980; Veraverbeke *et al.*, 2017; Du *et al.*, 2024).本研究引用大气CO_2含量变化作为雷暴频率的代表.

3.2 晚三叠世不同阶段古野火分布特征及控制因素

3.2.1 卡尼期 三叠纪卡尼期之前，陆地植被的分散性与单一性限制了野火的发生与蔓延，全球古野火记录较为稀缺(Scott, 2010; Abu Hamad *et al.*, 2012; Uhl *et al.*, 2012a; Kustatscher *et al.*, 2017).卡尼期古野火记录数量在晚三叠世与早侏罗世各个时期中最多，或许与该时期大气具有最高的pO_2有关(Mills *et al.*, 2023)，另一方面受Wrangellia大火成省(LIP)影响，pCO_2的逐渐升高促使卡尼期出现高温事件(图8)(Richards *et al.*, 1991; Svensen *et al.*, 2009; Dal Corso *et al.*, 2012, 2022; Trotter *et al.*, 2015; Sun *et al.*, 2016; Capriolo *et al.*, 2021)，此时高频率的闪电为古野火的发生提供主要点火源.古野火记录主要分布在北半球中低纬度

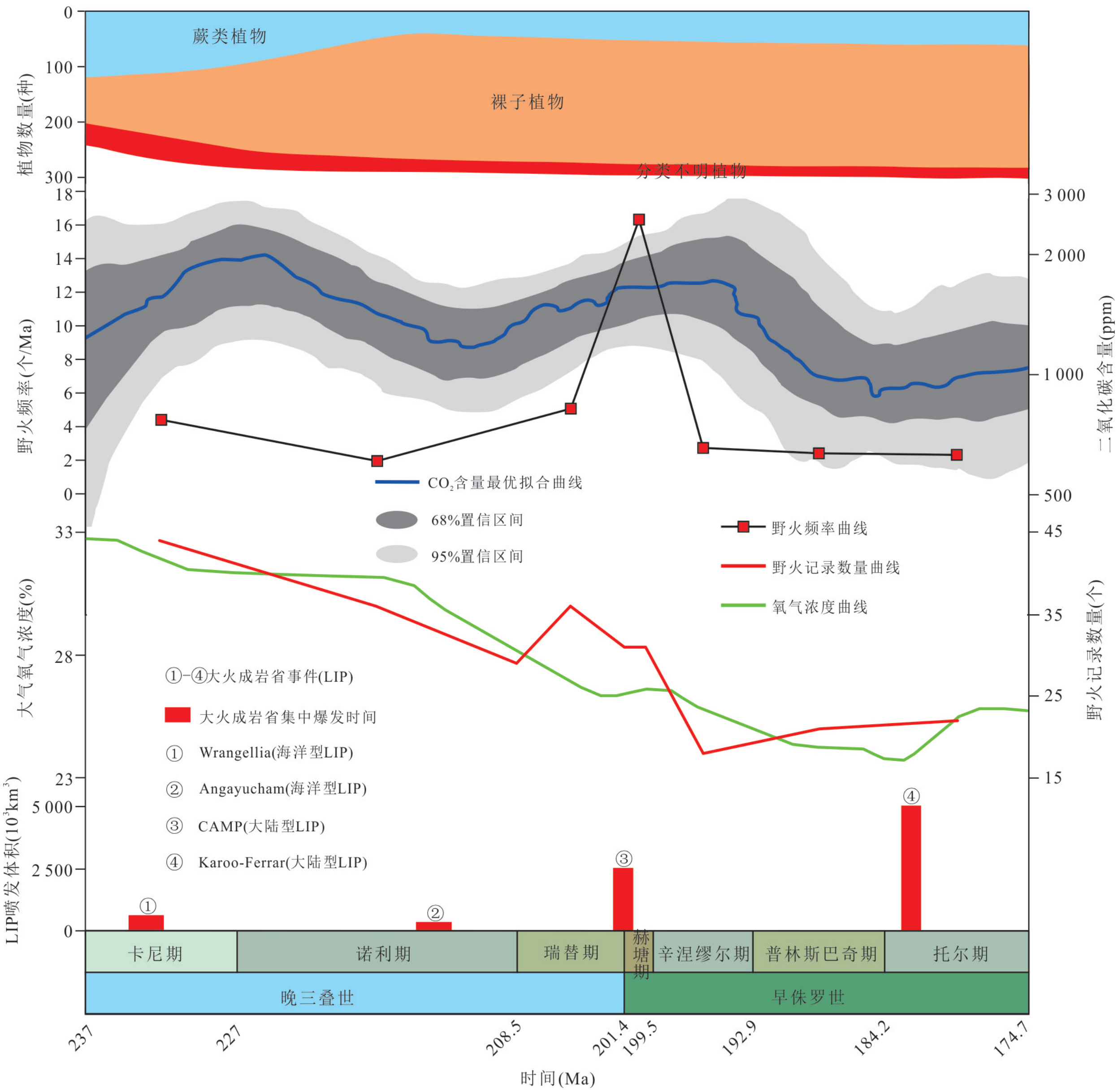

图 8　晚三叠世-早侏罗世各个时间段古野火事件记录及相关控制因素模式

Fig.8　Schematic diagram of paleowildfire event records and associated controlling factors from Late Triassic to Early Jurassic

大火成岩省喷发体积引自 Prokoph *et al.*（2013）；植物数量引自 Cleal and Cascales-Miñana（2014）；pCO_2 引自 Foster *et al.*（2017）；pO_2 引自 Mills *et al.*（2023）

热带地区与南半球中高纬度暖温带地区，干旱带少量分布（图 4a），可能受到卡尼期全球雨季事件（CPE）影响（Furin *et al.*，2006；Rigo *et al.*，2007；Dal Corso *et al.*，2015，2020；Sun *et al.*，2016；Miller *et al.*，2017）.CPE 时期全球水循环的显著增强，降雨量的增加为植物的繁盛提供良好的基础（Simms and Ruffell，1989；Dal Corso *et al.*，2018；Baranyi *et al.*，2019）. 位于南半球的冈瓦纳大陆大型植物群以球果蕨类为主，干热的古气候导致植物不甚发育，因此该地区的古野火事件较少发现（图 4a）. 位于北半球劳亚大陆植物群从喜旱向喜湿的微植物群和大型植物群转变（Pott *et al.*，2008；Roghi *et al.*，2010；Kustatscher *et al.*，2017），裸子植物逐渐占据陆地更多的生存空间，全球陆地植物种类逐渐增多（图 8），为古野火事件的发生提供了丰富的燃料.

3.2.2　诺利期　诺利期野火频率较卡尼期有所降低，古野火事件数量略微减少（图 8），主要发生在北半球中低纬度热带，暖温带地区与南半球中高纬度暖温带地区（图 4b）. 干旱带古野火记录较少与中低古纬度地区巨型季风系统导致的长期干旱，不利于

植物生长有关(Boucot *et al.*, 2013; Tanner, 2017; Bahr *et al.*, 2020).早中诺利期pO_2较高且保持稳定,而pCO_2从卡尼期至早诺利期呈持续上升趋势,于早诺利期达到顶峰(图8),这也是中生代pCO_2最高的时期(Foster *et al.*, 2017).高pCO_2使得热带与暖温带地区闪电频发,为古野火的发生提供大量点火源.

中诺利期延续到晚诺利期早期存在一个长达约五百万年极端温室期,全球升温幅度约6°C,海水表面最高温度曾高达35°C(Trotter *et al.*, 2015; Sun *et al.*, 2020; Chen *et al.*, 2024),此时更加耐旱的裸子植物迅速取代大部分蕨类植物,成为陆地植物的主要组成且种类更加丰富(图8),为古野火事件的发生提供更多燃料.随后高温及高湿度环境下硅酸盐的快速风化迅速消耗大气中CO_2,导致全球气温及海洋表层温度的快速下降,使晚三叠世在诺利期极端温室事件之后经历了一个快速变冷的阶段(Trotter *et al.*, 2015; Chen *et al.*, 2024).

晚诺利期pCO_2的升高与Angayucham大火成岩省(LIP)的爆发有关(Courtillot and Renne, 2003; Prokoph *et al.*, 2013).pO_2在中晚诺利期的同步降低可能也受到快速变冷阶段与Angayucham LIP的影响.另外,Angayucham LIP被认为是诺利期中晚期气候向湿润转换的主要驱动因素,具体而言,中诺利期至晚诺利期的气候湿度先缓慢增加,并在诺利末期气候湿度发生了显著增加(Ahlberg *et al.*, 2002; Hornung, 2005; Berra *et al.*, 2010; Haas *et al.*, 2012; Fijałkowska-Mader, 2015; Sato *et al.*, 2023).晚诺利期裸子植物与蕨类植物的占比逐渐趋于稳定,持续为古野火的发生提供燃料.

3.2.3 诺利期–瑞替期边界与瑞替期 诺利期–瑞替期边界古野火事件数量相较诺利期有所减少,作为两个时期的边界且野火记录数量仅略低于瑞替期,说明短时间内全球古野火频率较高,且主要分布在北半球中低纬度热带与暖温带地区(图4c).南半球暖温带地区古野火事件较少与巨型季风气候在该地区减弱,导致区域的植物分布减少有关(Cesar and Grice, 2019; Zeng *et al.*, 2019).pO_2呈迅速降低趋势,可能对诺利期–瑞替期边界海洋浮游生物的广泛灭绝产生影响(Orchard, 2010; Rigo *et al.*, 2017).裸蕨类植物种类占比相对稳定,CAMP集中爆发之前活跃的火山活动也可能促进pCO_2继续增长(图8)(Capriolo *et al.*, 2022),其引发的高频闪电也为古野火事件的发生提供大量点火源.

瑞替期野火频率较诺利期有明显升高,古野火事件数量也相较诺利期–瑞替期边界略微增加(图8),主要分布在北半球中纬度热带、北热带、干旱带与暖温带地区以及南半球低纬度热带地区,而南半球中纬度暖温带地区分布较少(图4d).从古地理位置上来看,古野火事件主要集中分布在欧亚板块、北美板块、南美板块和非洲板块的连接区域(图5).板块边界处多发的极端火山活动可能使得局部气候更加温暖干燥,促进古野火事件的发生,同时也可能间接导致了瑞替期海洋生物的逐渐灭绝(Lucas, 2010, 2018; Rigo and Joachimski, 2010; Dal Corso *et al.*, 2014; Trotter *et al.*, 2015; Todaro *et al.*, 2017, 2018).pO_2持续降低至晚瑞替期后保持稳定,pCO_2的急剧增加且全球温度上升则与CAMP大火成岩省事件引发的火山活动有关(图8)(Callegaro *et al.*, 2014; Capriolo *et al.*, 2020, 2022; Landwehrs *et al.*, 2020).高pCO_2导致的全球高频雷击与保持相对稳定裸蕨类植物分别为古野火事件的发生提供了点火源与燃料.

3.3 三叠纪–侏罗纪边界古野火分布特征及控制因素

3.3.1 古野火分布特征及控制因素 晚三叠世–早侏罗世之交,即瑞替期–赫塘期边界古野火事件主要分布在北半球中纬度热带、北热带、干旱带与暖温带地区,南半球分布较少(图5).作为两个时期的边界而非一整个时间段,古野火记录数量与赫塘期相等,说明短时间内全球古野火事件十分高频,且全球古野火记录的数量与空间分布在地理位置上和瑞替期极为相似,即古野火事件集中在北半球中纬度的板块连接区域.此时pO_2与全球植物种类数量均保持稳定,在此不作为全球古野火事件发生变化的决定性因素(图8).受中大西洋火成岩省爆发影响,pCO_2的持续上升(Callegaro *et al.*, 2014; Capriolo *et al.*, 2020, 2022; Landwehrs *et al.*, 2020).

中大西洋火成岩省(CAMP)跨越三叠纪末期与侏罗纪初期((201.64±0.03~201.36±0.02) Ma),覆盖了约1 000万平方公里的赤道区域(Blackburn *et al.*, 2013; Davies *et al.*, 2017, 2021; Marzoli *et al.*, 2019).岩浆活动可通过高温物质(如火山碎屑流、熔岩流、热火山灰)点燃周边植被(Tunison *et al.*, 2000; Abarzúa *et al.*, 2016; Pausas, 2016),而火山喷发产生的静电或冲击波可能触

发闪电，进一步扩大火灾范围（Scott, 2010）. 另外，大规模岩浆活动释放的温室气体（如CO_2、SO_2）可能导致区域升温与降水格局改变，增强植被季节性干旱，提高燃料易燃性（Hinojosa *et al.*, 2015）. 火山灰带来的营养物质（如磷、钾）也可能促进植物生长，增加燃料积累，为后续火灾提供物质基础（Shen *et al.*, 2011b; Cai *et al.*, 2021b）.

CAMP期间，富含CO_2和SO_2的玄武岩岩浆以短暂的脉冲形式喷发，大范围的岩浆活动可能在点燃植被的同时也引起局部温度迅速上升，使气候环境更加干燥，进一步促进野火事件多发（Knight *et al.*, 2004; Prokoph *et al.*, 2013; Hinojosa *et al.*, 2015; Heimdal *et al.*, 2019; Marzoli *et al.*, 2019; Capriolo *et al.*, 2021）. 同时引发了pCO_2的急剧增加和全球温度上升，促使雷击事件频发，间接为全球古野火事件提供大量点火源（图8）（Landwehrs *et al.*, 2020; Capriolo *et al.*, 2022）. 并伴随着严重的环境变化，浅海经历了缺氧-硫化以及海洋酸化，陆地上则发生广泛的野火、大陆风化增强、全球变暖和土壤流失等（McElwain *et al.*, 1999; Greene *et al.*, 2012; Van De Schootbrugge and Wignall, 2016; Van De Schootbrugge *et al.*, 2020; Fox *et al.*, 2022; Shen *et al.*, 2022; Bond *et al.*, 2023），环境变化与CAMP事件共同促使了三叠纪末期大灭绝事件（ETE）（(201.51±0.15～201.36±0.15) Ma）的发生（Whiteside *et al.*, 2008, 2010; Schoene *et al.*, 2010; Wotzlaw *et al.*, 2014; Zaffani *et al.*, 2018）.

惰质组反射率与含量（$\%R_o$）可定量反演燃烧温度与野火频率（Jones and Scott, 1991），结构惰质组（f+sf）与碎屑惰质组（i+m）的比值可指示燃烧植被类型（Scott, 1989）. 瑞典、丹麦盆地三叠纪-侏罗纪（T-J，约2.014亿年）界线的研究显示，瑞替期煤层惰质组平均含量仅17%，反射率区间3.64～4.95% R_o对应613～767 ℃的燃烧温度，(f+sf)/(i+m)比值为0.40～0.69，指示以针叶林木质植被的低频高温冠层火为主（Petersen and Lindström, 2012）. 进入赫塘期后，惰质组平均含量骤升至66%～75%，反射率降至1.26～1.56%R_o对应332～368 ℃的低温区间，(f+sf)/(i+m)比值低至0.04～0.24，指示草本、灌木植被的高频地表火（Petersen and Lindström, 2012）. 该认识得到了跨区域验证：格陵兰东部Astartekløft剖面赫塘期木炭丰度较瑞替期上升5倍，波兰同期地层同时记录了木炭富集与热成因多环芳烃，进一步证实赫塘期野火活动频率高于瑞替期（图8; Belcher *et al.*, 2010a）. 野火频率陡升主要受两方面驱动：一是T-J界线中大西洋岩浆省火山活动导致大气CO_2浓度从瑞替期至赫塘期持续上升，全球升温最高达4 ℃，上层对流层水汽含量上升使闪电活动频率提升，点火源显著增加（Price and Rind, 1994; Belcher *et al.*, 2010a; Denis *et al.*, 2017）. 二是植被易燃性整体增强，升温事件驱动植被从阔叶类群主导向窄叶类群组合转变，窄叶类群点火时间更短、燃烧热值更高，为野火的高频蔓延提供了燃料基础（Belcher *et al.*, 2010a; Petersen and Lindström, 2012）.

从晚三叠世末期的诺利期-瑞替期边界至瑞替期-赫塘期边界，在较短的时间边界内古野火记录连续且数量较多，表明CAMP在集中爆发前后可能通过活跃的火山活动释放大量温室气体，使得区域气候从温暖湿润趋向干旱炎热转变（Svensen *et al.*, 2004, 2012; Dera *et al.*, 2009; Hinojosa *et al.*, 2015; Lee and Dee, 2019），促进古野火事件发生. 且古野火记录不仅集中分布于暖温带与热带，靠近CAMP的北半球中纬度干旱带与北热带中也有明显分布（图2c、图5），这可能与CAMP相关的火山活动通过高温物质（如火山碎屑流、熔岩流、热火山灰）点燃周边植被有关（Tunison *et al.*, 2000; Abarzúa *et al.*, 2016; Pausas, 2016），全球古野火事件可能受CAMP与局部气候带的共同影响.

3.3.2　碳同位素负偏移与古野火活动相关性　中国准噶尔盆地南缘郝家沟剖面记录了两期显著的碳同位素负偏移事件（图9），其初始负偏移（I-NCIE）出现在上三叠统郝家沟组，与三叠纪末生物大灭绝（ETE）层位一致，$\delta^{13}C$偏移值约为$-0.7‰$，主负偏移（M-NCIE）发生于下侏罗统八道湾组，位于三叠系-侏罗系界线（TJB）之上，偏移幅度达$-1.7‰$（侯海海等，2023；张华杰，2023）. 类似的碳同位素负偏移现象于全球多个TJB界线剖面被发现，如意大利Pignola-Abriola剖面、奥地利Lorüns剖面与Kuhjoch剖面、英格兰St. Audrie's Bay剖面及美国Canyon剖面等（图9a～9e），指示其受控于全球性环境事件扰动（Zaffani *et al.*, 2018; Wignall and Atkinson, 2020；张新智等，2022）.

碳同位素负偏主要源于大气中轻碳（^{12}C）的快速增加，中大西洋火成岩省（CAMP）火山喷发释放巨量富^{12}C的CO_2是导致全球碳循环扰动和同位素负偏的主要因素. 同时，陆生植被燃烧释放的含^{12}C

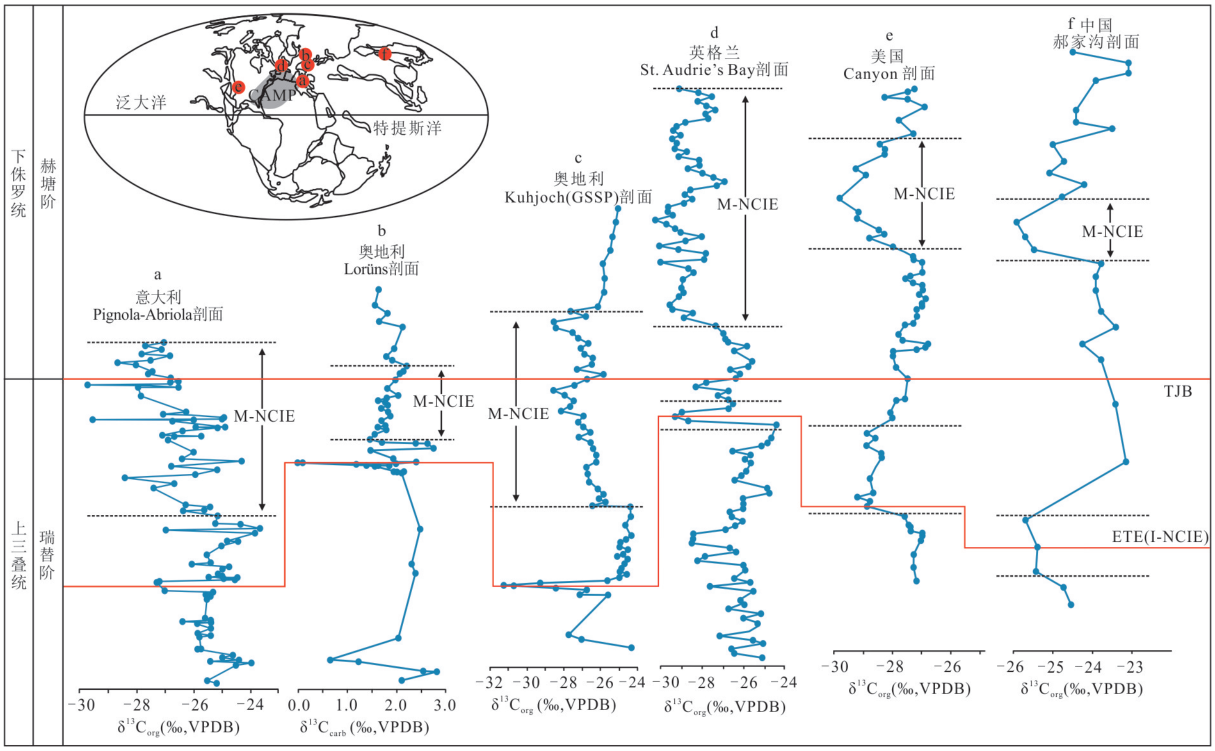

图9 全球典型TJB剖面碳同位素负偏移对比(据侯海海等, 2023修改)

Fig.9 Comparison of negative carbon isotope excursions in globally representative Triassic-Jurassic boundary sections

温室气体可能进一步加剧负偏程度(图9)(Ruhl *et al.*, 2011; Heimdal *et al.*, 2018; Song *et al.*, 2020).

晚三叠世-早侏罗世边界碳同位素负偏事件发生期间,全球气候呈现暖湿-干热变化趋势(张华杰, 2023).CAMP火山活动释放的CO_2与CH_4气体增强了温室效应,引起气温上升和蒸发加剧,部分地区趋于干旱.干旱气候使植被易燃性增加,同时高温可能提升闪电频率(Price and Rind, 1994; Belcher *et al.*, 2010a; Denis *et al.*, 2017),提供大量点火源,促使古野火活动多发(Reeve and Toumi, 1999; Thibodeau *et al.*, 2016; Song *et al.*, 2020).古野火通过燃烧植物有机质,产生CO_2与CH_4并释放至大气,引起$\delta^{13}C$值降低,从而加剧碳同位素负偏移(图9).另一方面,野火导致陆地植被覆盖减少,削弱了光合作用对^{13}C的吸收与固定,进一步扰乱全球碳循环.在郝家沟剖面,I-NCIE与M-NCIE层段中作为燃烧产物的惰质组含量显著增高,且与碳同位素负偏表现出良好的同步性,表明碳同位素负偏受到古野火活动影响(侯海海等, 2023).

在全球多个TJB剖面(如欧洲、中国和格陵兰岛)中,普遍发现了木炭、高含量惰质组以及多环芳烃(PAHs)等古野火标志物(图4~图6),且这些记录往往与碳同位素负偏移层位比较一致(Marynowski and Simoneit, 2009; Williford *et al.*, 2014; Song *et al.*, 2020; 张新智等, 2022; 侯海海等, 2023),表明碳同位素负偏移不仅与火山活动有关,也响应于全球频发的古野火事件.全球不同地区碳同位素负偏移幅度存在明显差异(图9).靠近CAMP火山区的奥地利Lorüns剖面与Kuhjoch剖面I-NCIE幅度显著大于M-NCIE,可能反映火山直接排放轻碳的主导作用,而远离CAMP的准噶尔盆地则M-NCIE偏移幅度更大,反映古野火燃烧对碳同位素组成的叠加影响,表明在远离火山活动的区域,古野火事件对碳同位素负偏的贡献更为显著(Ruhl *et al.*, 2010; Felber *et al.*, 2015; Hu *et al.*, 2020).

综上所述,晚三叠世-早侏罗世界线附近的碳同位素负偏移事件主要源于CAMP火山作用,由于火山活动所引发的气候变暖与干旱化显著促进了古野火发生,古野火事件通过排放轻碳和破坏植被碳库进一步加剧负偏移,从而使得碳同位素负偏与古野火记录表现出良好的时空耦合关系(Belcher *et al.*, 2010b; Glasspool *et al.*, 2015; Heimdal *et al.*, 2018),与其他古野火标志物(木炭、惰质组、多环芳烃)共同指示了全球古野火事件在三叠纪与侏罗纪边界处广泛发生.

3.4 早侏罗世不同阶段古野火分布特征及控制因素

3.4.1 赫塘期与辛涅缪尔期　赫塘期野火频率较瑞替期显著增高且达到整个晚三叠世-早侏罗世的最大值，可能受到CAMP火山活动、pCO_2持续上升与pO_2缓慢回升的共同影响（图8），为古野火的发生提供良好的点火源与助燃条件（Landwehrs *et al.*, 2020；Capriolo *et al.*, 2022）. 古野火事件数量与瑞替期-赫塘期边界持平，主要集中分布在北半球中纬度北热带与暖温带地区，这或许与温带气候显著的季节性变化和干湿条件的变化有利于古野火的点燃和发生有关（Lu *et al.*, 2021；Baker, 2022；Vitali *et al.*, 2022）. 在南半球中低纬度暖温带，热带地区与北半球低纬度热带地区古野火记录较少，干旱带地区零星分布（图 6a）. 温暖湿润的气候更有利于植被的生长，此时稳定生长的裸子植物与蕨类植物为热带地区规律性古野火的发生提供大量燃料，而干旱气候通常不利于植物生长，常常导致干旱带地区缺乏足够的燃料，因此干旱带古野火发生率低于热带与暖温带地区（Uhl *et al.*, 2012b；Denis *et al.*, 2017；Baker, 2022；Vitali *et al.*, 2022）.

辛涅缪尔期野火频率较赫塘期出现大幅度降低，古野火记录在晚三叠世至早侏罗世各个时期中最少，主要分布在北半球中纬度暖温带与北热带地区，南半球中低纬度热带、暖温带地区呈零星分布（图 6b）. 裸子植物与蕨类植物的种类数量在整个早侏罗世持续稳定，因此可不作为影响古野火事件变化的决定性因素（图 8）. 早中辛涅缪尔期pCO_2持续增加，至晚辛涅缪尔期达到最高值，晚辛涅缪尔期出现温暖期（Hesselbo *et al.*, 2000；Gómez *et al.*, 2016），而海侵相序表明的冷却现象可能完全抵消了当时的全球变暖，全球气候从普遍温暖转变为普遍寒冷（Korte and Hesselbo, 2011；Du *et al.*, 2024），同时整个辛涅缪尔期pO_2呈显著的持续降低趋势，可能更加抑制了辛涅缪尔期古野火事件的发生.

3.4.2 普林斯巴奇期与托尔期　普林斯巴奇期野火频率较辛涅缪尔期基本持平，古野火事件主要分布在北半球中纬度北热带与暖温带地区，南半球中纬度暖温带地区少量分布，热带与干旱带地区零星分布（图 6c）. 早普林斯巴奇期的高pCO_2可能导致短暂的升温期出现，为古野火事件的发生提供气候条件，促使普林斯巴奇期古野火记录数量较辛涅缪尔期出现增长（Gómez *et al.*, 2016）. 随后pCO_2与pO_2出现持续降低，这可能导致晚普林斯巴奇期出现全球性大规模的降温，使得普林斯巴奇期古野火事件相对较少（Dera *et al.*, 2011；Gómez and Goy, 2011；Suan *et al.*, 2011；Fraguas *et al.*, 2012；Gómez *et al.*, 2016）.

托尔期野火频率与辛涅缪尔期和普林斯巴奇期基本相同，古野火事件数量较普林斯巴奇期有所增加，主要分布在北半球中纬度北热带、暖温带地区，南半球中低纬度热带、暖温带地区少量分布，干旱带地区零星分布（图 6d）. 早托尔期 Karoo-Ferrar 大火成岩省爆发，大量火山CO_2、热生成甲烷（CH_4）等气体的释放导致pCO_2重新转为增长趋势（Hesselbo *et al.*, 2000；McElwain *et al.*, 2005；Seton *et al.*, 2012；Burgess *et al.*, 2015），与快速增长的pO_2共同作用，可能使水文循环增强与雷击频发，气候也从普遍凉爽转变为普遍温暖，促进了针叶树的繁殖与古野火事件的增加（Baker *et al.*, 2017；Xu *et al.*, 2017；Slater *et al.*, 2019；Lu *et al.*, 2021；Silva *et al.*, 2021；Du *et al.*, 2024）. 同时，气候和环境因素的综合作用也导致了早托尔期海洋缺氧事件与海洋生物大规模灭绝（Wignall *et al.*, 2005；Jenkyns, 2010；Ullmann *et al.*, 2014；Them *et al.*, 2017；Hesselbo *et al.*, 2020）.

3.5 晚三叠世至早侏罗世全球古野火事件分布的地质控因及模式

整体上，晚三叠世-早侏罗世全球古野火发生的次数和频率与pO_2和pCO_2关系密切，晚三叠世古野火记录数量显著多于早侏罗世，这或许与其pO_2显著高于早侏罗世有关；而pCO_2和野火发生频率从晚三叠世至早侏罗世则呈现出相似的变化趋势（图 8）. 另外古地理是植物生长的物质基础，而古气候又影响着古植物的生长和演替，再叠合该时期多个大型地质事件，最终形成了晚三叠世-早侏罗世全球古野火事件时空分布的地质控因及模式图（图 8）.

3.5.1 古地理　晚三叠世与早侏罗世古野火记录南北半球分布呈现显著的不对称性：北半球（30°N～60°N）古野火记录远多于南半球（图 4～6），仅卡尼期古野火事件南北半球分布较为均匀（图 2b、图 3a）. 北半球野火证据记录较多亦见于其他时期，可能是北半球中纬度地区的陆地面积较大、具有较强的古野火发生物质基础所导致（Abu Hamad *et al.*, 2012；Brown *et al.*, 2012；Boucot *et al.*, 2013）. 广阔的陆地面积更适应植物生长，同时植物不完全燃

烧的产物可以形成煤中惰质组,晚三叠世与早侏罗世拥有众多重要的成煤区且主要分布在北半球(如中国侏罗纪煤炭储量占其总量三分之二),进一步导致了古野火记录在南北半球较强的差异性(Boucot *et al.*, 2013; Shao *et al.*, 2020).这些因素在一定程度上解释了北半球野火记录显著多于南半球的现象.另外三叠纪和侏罗纪之交古野火事件频发受到中大西洋火成岩省(CAMP)及其前后多发的火山活动影响.瑞替期与瑞替期-赫塘期边界(晚三叠世-早侏罗世边界),古野火事件不仅集中于暖温带与热带,且在靠近CAMP的北半球干旱带和北热带地区大量分布.

3.5.2 古植物 古野火记录的空间分布基本与晚三叠世和早侏罗世植物群的全球分布比较吻合.晚三叠世呈现显著的纬度梯度模式,低纬度区(如欧洲、北美)以松柏目、盾籽目等高大裸子植物乔木为主(Axsmith *et al.*, 2004),中纬度区(如阿根廷、巴西)优势种为中型与小型裸子植物,如盔籽目和叉羽叶属(Abu Hamad *et al.*, 2008; Mancuso, 2009),高纬度区(如南极)植物群则以蕨类、石松类为主,伴生少量裸子植物(Cantrill *et al.*, 1995; McLoughlin *et al.*, 1997).此分布模式与晚三叠世全球气候分带低纬度干旱-半干旱、中高纬度温暖湿润密切相关(Preto *et al.*, 2010),且晚三叠世古野火记录主要分布在中低纬度地区可能与该区域中大型裸子植物的繁盛有关.晚三叠世与早侏罗世时期低纬度地区为以广阔沙漠为主的干旱带,且经历了不利于陆生植物生存的极端高温,燃料匮乏促使低纬度干旱带古野火稀少(Scotese, 2016; Li *et al.*, 2024).早侏罗世低纬度带以具厚角质层的微叶型苏铁类和松柏类为主,对季节性干旱适应性较强(Vakhrameev, 1991; Rees *et al.*, 2000),中纬度带植被最丰富多样,以蕨类、楔叶类、大叶型苏铁类及松柏类为特征,反映温暖湿润温带气候,是全球植物生产力和多样性中心,高纬度带则以可能为落叶型的大叶型松柏类和银杏类为主,比较适应季节性光照不足与凉爽气候(Ziegler, 1996; Rees *et al.*, 2000).早侏罗世各个时期古野火记录主要集中于中纬度地区则可能与该区域植被类型最为丰富有关.

3.5.3 古气候 基于Boucot *et al.*(2013)的古气候带划分,晚三叠世卡尼期至诺利期-瑞替期边界古野火证据主要集中在暖温带与热带,而瑞替期与瑞替期-赫塘期边界的古野火事件在暖温带,北热带,干旱带,热带四个气候带中呈相对均匀分布.早侏罗世古野火事件主要分布在暖温带与北热带(图2c).干旱气候常常由于植被稀疏、燃料匮乏而野火较少,而温暖湿润环境利于植被繁盛,产生丰富可燃物,易引发规律性或间歇性野火(Uhl *et al.*, 2012b; Denis *et al.*, 2017; Baker, 2022; Vitali *et al.*, 2022).作为主要自然火源,闪电在湿润气候更频发(Cope and Chaloner, 1980; Renkin *et al.*, 1992; Veraverbeke *et al.*, 2017; Brey *et al.*, 2018).温带气候显著的季节性干湿变化进一步促进了野火发生(Lu *et al.*, 2021).因此,晚三叠世热带、暖温带与早侏罗世暖温带、北热带地区古野火频发,主要归因于气候-植被的协同作用.而靠近三叠纪-侏罗纪界线的瑞替期与瑞替期-赫塘期边界,古野火事件不只集中在热带与暖温带,在干旱带与北热带中同样大量分布,其原因可能是受CAMP相关的火山活动直接点燃与局部气候带的共同影响.

3.5.4 地质事件 整体而言,不同时期的大型地质事件对全球气候与古野火事件有重要控制作用,多次出现的大火成岩省事件在一定程度上促使极端气候的产生,如全球性雨季,极端温室效应等,间接影响了古野火事件与大灭绝事件的发生(Dal Corso *et al.*, 2012, 2020; Prokoph *et al.*, 2013; Davies *et al.*, 2017; Cesar and Grice, 2019; Fox *et al.*, 2022; Chen *et al.*, 2024).晚三叠世初期,受Wrangellia LIP影响,大气pCO_2快速上升使全球出现高温事件,与快速繁盛的植物和较高的大气氧气浓度,共同促进了卡尼期高频野火事件的发生;大气pCO_2于早诺利期达到最高值,耐旱的裸子植物更加繁盛,之后pCO_2出现几乎横跨诺利期的下降阶段,使中诺利期经历极端温室事件之后进入到快速变冷阶段,与快速降低的pO_2共同抑制了诺利期的野火频率;随后Angayucham LIP事件与CAMP爆发相关的频繁火山活动依次促进了大气pCO_2的重新缓慢回升,使pCO_2的上升阶段跨越了诺利期-瑞替期边界、瑞替期、瑞替期-赫塘期边界(晚三叠世-早侏罗世边界)、赫塘期与辛涅缪尔期,于辛涅缪尔期末期达到最大值.该阶段初期伴随裸子植物与蕨类植物的占比趋于稳定,促进了诺利期-瑞替期边界与瑞替野火频率的升高;该阶段后期,受CAMP集中爆发影响瑞替期-赫塘期边界与赫塘期全球野火频率快速增加,共同促进了三叠纪末期大灭绝事件(ETE)的发生,多个T-J剖面碳同位素负偏移现象

响应了高频野火的全球性．pCO_2上升至辛涅缪尔期中期向下降转变，全球野火频率骤降，或许与大气pO_2持续降低，且晚辛涅缪尔期全球气候从普遍温暖转变为普遍寒冷有关．随后pCO_2呈下降趋势至早托期Karoo-Ferrar LIP爆发才出现缓慢回升，持续降低的pCO_2与大气pO_2抑制了普林斯巴奇期的野火频率，而一直处于低位pCO_2的托尔期，在大气pO_2出现增长的作用下使得野火数量略高于普林斯巴奇期，野火频率则十分接近．

4 结论与展望

（1）在全球晚三叠世至早侏罗世的地层记录中，共发现木炭、惰质组及热解多环芳烃所指示的古野火记录268条，野火频率最高时期为早侏罗世赫塘期，最低时期为晚三叠世诺利期．空间格局上，野火分布存在明显纬度分异与半球差异：卡尼期至诺利期-瑞替期边界：野火集中于北半球中低纬度热带、暖温带区域，仅卡尼期在南半球暖温带存在相对较多记录；瑞替期至三叠-侏罗系（T-J）边界：野火在北半球中纬度热带、北热带、暖温带、干旱带呈均匀分布，南半球中纬度暖温带记录较少；早侏罗世野火集中分布于北半球中纬度暖温带与北热带区域，热带与干旱带记录较少．

（2）晚三叠世和早侏罗世古野火活动受控于pCO_2、pO_2、植被和大型地质事件共同影响．①晚三叠世初期受高pCO_2、高pO_2、叠加全球雨季事件（CPE）驱动的植被繁盛共同促使卡尼期野火频发，随后pCO_2持续下降与pO_2同步降低，抑制了诺利期野火活动．后续pCO_2出现跨T-J边界的长时间持续回升阶段，植被群落结构趋于稳定且火山活动频繁，促使诺利期-瑞替期边界、瑞替期、瑞替期-赫塘期边界及赫塘期野火频率呈升高趋势．辛涅缪尔期受pCO_2逐步向下降转变、pO_2持续降低与气候转冷影响，野火频率骤降．早侏罗世中晚期pCO_2整体处于低位，仅托尔期pO_2回升使得野火数量略高于普林斯巴奇期，野火频率稳定不变．

（3）受CAMP集中爆发影响，瑞替期-赫塘期边界（T-J边界）与赫塘期全球野火频率快速增加，显著高于晚三叠世与早侏罗世其他时期，多个T-J剖面碳同位素负偏移现象响应了该时期高频野火的全球性，古野火作用下的陆地植被系统瘫痪为三叠纪末期大灭绝事件（ETE）提供了有利条件．

前人对于全球晚三叠世和早侏罗世古野火事件的研究已经取得了长足的进步，但仍需要在以下几个方面进行深入分析：①高精度年代框架下的古野火时空序列重建：探索TJB古野火变化与生物环境协同关系需要高精度年代学和高分辨率地层重建为基础，因此TJB全球海相地层和陆相地层高精度年代学研究及地层对比仍是将来工作的重点．在此基础上建立野火事件与火山活动、气候突变更加精确的时间框架，明确"火山喷发-气候波动-野火爆发"的直接作用机理．②多指标集成和相互交叉验证分析：现有研究主要依赖木炭、惰质组与热解多环芳烃三类证据，但不同指标对野火的响应灵敏度、保存条件存在差异．未来可整合汞同位素、炭屑形态、植硅体烧失特征等新兴指标，建立多指标交叉验证的野火识别体系，提高古野火事件识别的精准度与可信度．

附表见https://doi.org/10.3799/dqkx.2026.194.

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