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晚三叠世诺利期极端温室期地质事件

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摘 要: 晚三叠世诺利期存在一个极端温室期,从中诺利期延续到晚诺利期早期,低纬度地区海水表层最高温度曾高达35 ℃,极高温期发生在牙形石 *Mockina bidentata* 带下部所代表的时限.诺利期极端温室期海洋和陆地上伴随着重要的生物演化事件,干湿气候的变化在不同地区表现并不完全一致.该时期发生了全球板块运动、火成岩省活动、火流星、地球化学指标显著变化等众多事件.这些事件的全球意义、潜在的因果关系以及在东特提斯的响应等亟需研究.我国发育有良好的诺利期地层序列,是东特提斯地区研究这一极端温室期气候变化与生物演化的理想区域.

关键词: 诺利期;极端温室;联合古陆;晚三叠世;特提斯;地层学;气候变化.

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Geological Events during the Extreme Greenhouse Interval of Norian, Late Triassic

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Abstract: An extreme greenhouse interval existed in the Norian of Late Triassic, lasted from the Middle Norian to the early Late Norian. The maximum sea surface temperature in low latitudes can reach 35 ℃ during the extremely high temperature interval occurred in the lower part of the conodont *Mockina bidentata* Zone. The extreme greenhouse interval of the Norian was accompanied by important biological evolution events in the ocean and land. The changes of dry and wet climate were not completely consistent in different regions. Many events occurred in this interval, such as global plate movement, igneous province activity, bolide and significant changes of geochemical indexes. The global significance of these events, their potential causality, and the response in the East Tethys need to be further studied. China has a good Norian stratigraphic sequence, which is an ideal area to study the climate change and biological evolution of this extreme greenhouse interval in the East Tethys region.

Key words: Norian; extreme greenhouse; Pangaea; Late Triassic; Tethys; stratigraphy; climate change.

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1 晚三叠世诺利期极端温室期

研究地质历史上极端温室期的气候变化及相应的生物演化对逐渐变暖的当今社会具有重要的启示意义.三叠纪是地质历史上一个重要的温室时期(Trotter *et al.*, 2015; Song *et al.*, 2019; Grossman and Joachimski, 2022).经历古-中生代之交的显生宙最大的生物灭绝(Erwin, 1993)事件之后,早三叠世以环境动荡为特点(Payne *et al.*, 2004),中三叠世则是气候改善和复杂生态群落恢复和重建时期(Erwin, 1993; Bottjer, 2004; Chen and Benton, 2012).晚三叠世也是生物演化历史上关键转折时期.Dal Corso *et al.*(2020)基于化石记录的分析研究认为晚三叠世卡尼期雨季事件(Carnian Pluvial Episode)虽然导致了生物灭绝事件,但也可能引发了许多主导现代生态系统的关键种群的辐射(Simms and Ruffell, 1990; Tanner *et al.*, 2004; Lucas and Tanner, 2004; Demangel *et al.*, 2020; Dal Corso *et al.*, 2020, 2022; Rigo *et al.*, 2020; Dunne *et al.*, 2021),被视作当今地球生态系统的黎明.

Trotter *et al.*(2015)根据牙形石磷灰石测量的氧同位素($\delta^{18}O_{phos}$)重建了三叠纪海洋表面温度,提出了三叠纪存在三次极端温室事件(Warm event).分别是早三叠世温室事件(W1)、晚三叠世卡尼期温室事件(W2)和晚三叠世晚诺利期温室事件(W3).其中来自西特提斯 Lagonegro 盆地(见图 1,红五星)的数据显示牙形石 $\delta^{18}O_{phos}$ 的氧同位素值在晚诺利期牙形石 *Mockina bidentata* 带内可低至 18.29‰,据此估算的古海水表面温度最高可达 33.5 °C,升温幅度约 7 °C(Trotter *et al.*, 2015).而来自联合古大陆(Pangaea)西部 Williston Lake(见图 1,橙五星)的牙形石磷灰石 $\delta^{18}O_{phos}$ 值也证实了从 Alaunian(中诺利期)到 Sevatian(晚诺利期)存在一个极端温室期,升温幅度约 6 °C,海水表面最高温度曾高达 35 °C(Sun *et al.*, 2020).同样的,对东特提斯保山地块(见图 1)的晚诺利期牙形石 *Mockina bidentata* 带内牙形石 $\delta^{18}O_{phos}$ 的氧同位素研究显示,该时期海水表面最高温度也曾高达约 35 °C(Chen *et al.*, 2024,黄五星).这些研究指示晚三叠世诺利期存在一个极端温室期,可能从中诺利期延续到晚诺利期早期,时间长达五百万年,极高温期发生在牙形石 *Mockina bidentata* 带下部所代表的时限(图 2).

2 晚三叠世诺利期极端温室期生物演化

诺利期极端温室期,特别是中-晚诺利期之交,许多生物类群发生了重要转变.Lucas(2018b)总结认为晚三叠世大多数大型两栖动物在诺利期末灭绝.在爬行动物中,中三叠世至晚三叠世卡尼期繁盛的食草动物喙龙和二齿兽最终在晚诺利期灭绝(Spielmann *et al.*, 2013; Racki and Lucas, 2020).Baranyi *et al.*(2018)通过对美国西南部 Chinle 组的孢粉数据进行定量分析,发现在中-晚诺利期之交,植

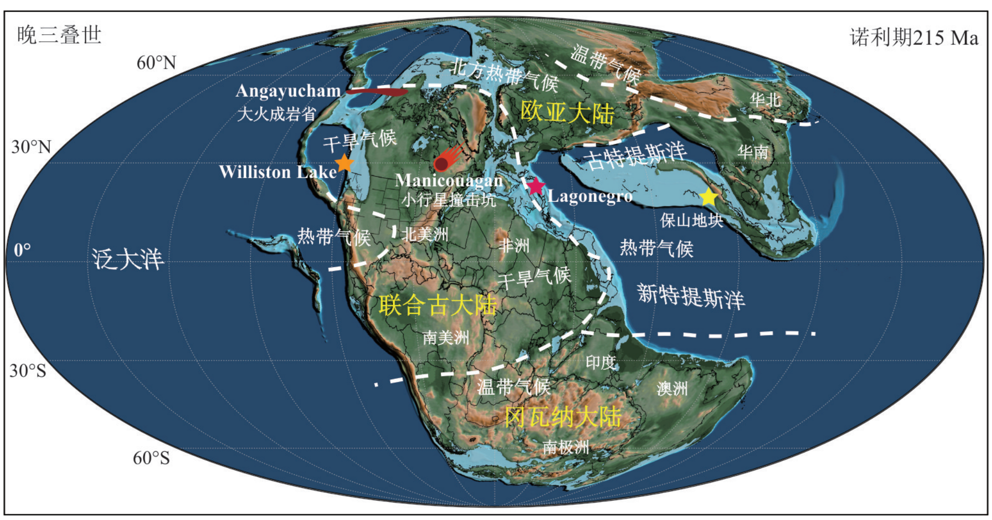

图 1 晚三叠世诺利期全球古地理图

Fig.1 Global paleogeographic map of the Late Triassic Norian

图修改自 Boucot *et al.*(2013)、Scotese(2021);五角星代表古海水温度重建研究区,红色代表 Trotter *et al.*(2015)研究的西特提斯区域,橙色代表 Sun *et al.*(2020)研究的北美地区,黄色是 Chen *et al.*(2024)研究东特提斯保山地区

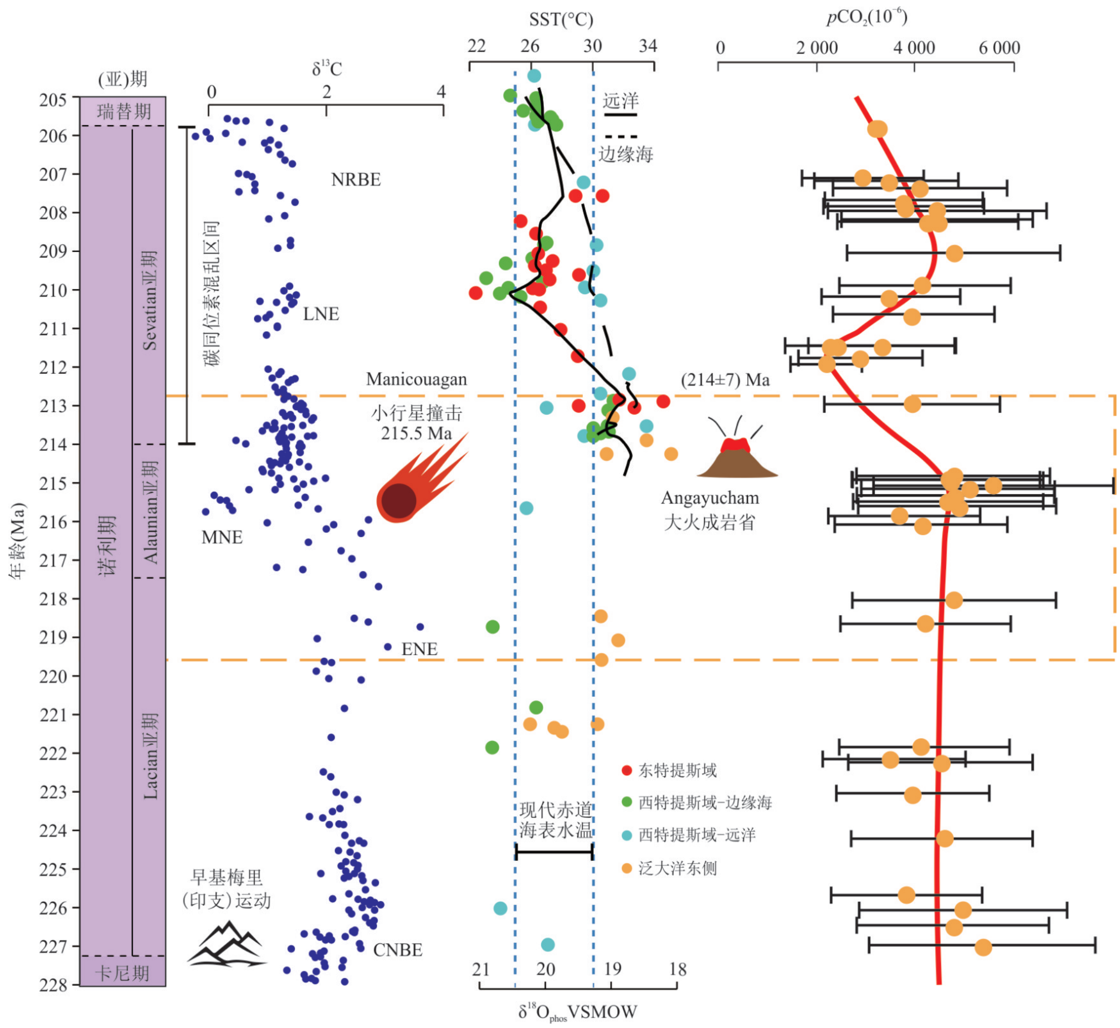

图 2　诺利期极端温室期重要环境地质事件时间坐标

Fig.2　Time coordinates of important environmental geological events during the extreme greenhouse of the Norian

地质年代表来自 Ogg *et al.*(2020);碳同位素来自 Cramer and Jarvis(2020);CNBE:Carnian-Norian Boundary Event,卡尼阶-诺利阶界线附近碳同位素偏转事件;ENE:Early Norian Event,早诺利期碳同位素偏转事件;MNE:Middle Norian Event,中诺利期碳同位素偏转事件;LNE:Late Norian Event,晚诺利期碳同位素偏转事件;NRBE:Norian-Rhaetian Boundary Event,诺利-瑞替阶界线附近碳同位素偏转事件;Manicouagan 小行星撞击年龄来自 Ramezani *et al.*(2005);牙形石磷灰石氧同位素以及海表水温(SST,Sea surface temperature)重建来自 Trotter *et al.*(2015)、Sun *et al.*(2020)、Du *et al.*(2021)、Chen *et al.*(2024);Angayucham 大火成岩省年龄来自 Prokoph *et al.*(2013);大气二氧化碳含量(pCO_2)来自 Knobbe and Schaller(2018);虚线方框指示极端温室气候区间

物组合出现了重大更替.Kent *et al.*(2019)、Hayes *et al.*(2020)基于美国亚利桑那州石化森林国家公园(Petrified Forest National Park)脊椎动物组合与高精度地质年代学和岩石地层学研究,通过建模分析发现该时期存在重要的脊椎动物类群转变.Kent and Clemmensen(2021)总结观察到蜥脚类恐龙从冈瓦纳大陆南半球的高纬度地区(巴西、阿根廷等地)迅速向北迁移扩散至北半球温带的欧洲以及格林兰岛地区.

海相生物中,McRoberts(2007,2010)观察到在中-晚诺利期之交 *Halobia* 属、*Eomonotis* 属的双壳类几乎全部消失,而 *Monotis* 属的双壳类开始出现,至诺利期-瑞替期之交,*Monotis* 属双壳类发生大灭绝,只有 2 个侏儒种(*Monotis hoernesi* 和 *Monotis rhaetica*)孑余.钙质超微浮游生物在 Sevatian 亚阶 *Mockina bidentata* 带发生演替和小型化(Preto *et al.*,2013;Demangel *et al.*,2020;Jia *et al.*,2024).Onoue *et al.*(2012,2016)观察到泛大洋的放射虫在 Sevatian 亚阶牙形石 *Epigondolella bidentata*(= *Mockina bidentata*)带内逐步灭绝,其组合发生重大更替(Onoue *et al.*,2016;Sato *et al.*,2020),多样性有明显的降低(O'Dogherty *et al.*,2010).Lucas

(2018a)总结前人关于菊石的研究后指出在诺利期Sevatian亚期,菊石多样性发生显著下降并且出现异态(heteromorphs).Rigo *et al.*(2020)总结前人研究指出,菊石在晚三叠世经历了两幕灭绝,第一幕灭绝发生在诺利期-瑞替期之交,第二幕则发生于瑞替期晚期.中诺利期(Alaunian亚期)牙形石动物群落通常由大量的幼体或者亚成年体标本组成,仅有少量的成年体标本(Martínez-Pérez *et al.*,2014;Karádi *et al.*,2020).

3 晚三叠世诺利期极端温室期的气候变化

晚三叠世,联合古大陆超级季风气候达到最强,气候总体上相对炎热干旱,但是常被湿润事件所打断,例如卡尼期中期的雨季事件.整个诺利期到瑞替期初,一个稳定的巨型季风气候系统使得联合古大陆内陆低到中古纬度的地区处于干旱状态(Boucot *et al.*,2013;Tanner,2018;Bahr *et al.*,2020)(见图1).但也有学者认为,在诺利期超过2 000万年的时间内,这种非常长时间的环境稳定性可能是由于缺乏详细的古气候研究造成的(Preto *et al.*,2010).近年来越来越多的证据显示全球很多区域在诺利期出现了明显的气候环境波动.Haas *et al.*(2012)提出中诺利期至晚诺利期的气候湿度可能逐渐增加,并在诺利末期发生了显著的气候变化从而导致湿度明显增加.波兰地区的孢粉记录亦表明在晚诺利期(Sevatian亚期)植物向喜湿类群转变,指示该时期有一个小型的湿润气候变化(Fijałkowska-Mader,2015).除此之外,位于欧洲的多个沿海地区,均有晚诺利期出现一次湿润气候或者开始向湿润气候转变的报道(Kent and Olsen,2000;Ahlberg *et al.*,2002;Hornung,2005;Berra *et al.*,2010;Haas *et al.*,2012,2017;Fijałkowska-Mader,2015),显示诺利期末期至瑞替期气候开始逐渐转变为更加湿润.Lepre and Olsen(2021)针对北美科罗拉多高原的Chinle组红层赤铁矿的研究表明在诺利期~215 Ma开始,古气候加剧干旱化,并表明在Adamanian-Revueltian脊椎动物转换期(216 Ma至213 Ma)时段降雨量发生了显著降低.除此之外,位于北美的多个晚诺利期内陆研究区,均有逐渐向干旱环境转变的报道(Nordt *et al.*,2015;Lepre and Olsen,2021).

晚三叠世在诺利期极端温室事件之后主要经历了一个快速变冷的阶段(Trotter *et al.*,2015;Chen *et al.*,2024)(图2).目前驱动这一变冷的详细模式和原因仍存在巨大争议,包括有因联合古大陆向北漂移造成赤道地区风化面积的增加(Golonka,2007),早基梅里-印支运动(Early Cimmerian-Indosinian Orogeny)引起的陆地风化强度的增加(Onoue *et al.*,2018),古特提斯闭合期联合古大陆汇聚顶峰时暴露的硅酸盐风化强度增强(Chen *et al.*,2024),颗石藻等钙质超微化石的繁盛(Goddéris *et al.*,2008),以及小行星撞击事件(Sato *et al.*,2020)等等.

4 晚三叠世诺利期极端温室期的其他地质事件

晚三叠世主要构造事件是早基梅里运动(Early Cimmerian Orogeny)和印支运动(Indosinian Orogeny)(图2).基梅里-印支造山运动是一个多阶段的造山运动,涉及基梅里微陆块群与欧亚大陆南缘的碰撞和构造相互作用.从二叠纪起,多个微陆块从冈瓦纳大陆北缘裂解,古特提斯洋达到最大化(吴福元等,2020;朱日祥等,2022).随着微陆块群的北向漂移,古特提斯洋逐渐消亡.基梅里微陆块群在晚三叠世开始与欧亚大陆南缘碰撞拼合,先是发生在欧洲的阿尔卑斯-喀尔巴阡-地中海地区,而后发生在东欧-中亚地区,最后发生在东南亚地区(Şengör *et al.*,2023).在这时期,东特提斯地区的印度支那、羌塘与华南等板块最终与地球上其他绝大多数板块汇聚在一起形成联合古大陆,关闭了古特提斯洋,随后早侏罗世联合古大陆开始出现裂解,标志着晚三叠世时联合古大陆达到其最大面积(Stampfli *et al.*,2013;Golonka *et al.*,2018).

晚三叠世发生了三次著名的大火成岩省活动,即:北美洲西北的Wrangellian玄武岩大火成岩省(约发生在230~225 Ma之间;Greene *et al.*,2010)、Angayucham大火成岩省(约发生于(214±7)Ma;Prokoph *et al.*,2013),以及中大西洋岩浆省(The Central Atlantic Magmatic Province,约发生在201 Ma前;Marzoli *et al.*,2018).晚三叠世卡尼期的高温事件(Trotter *et al.*,2015;Sun *et al.*,2016)被认为与Wrangellian大火成省大规模CO_2释放有关.中大西洋岩浆省(Central Atlantic Magmatic Province,CAMP)的火山活动曾被认为可能导致了W3等晚三叠世诺利期Alaunian至Sevatian的环境变化.但随着CAMP的最老喷发年龄确定于201.625 Ma

(Davies *et al.*, 2017),该火山活动多被认为是三叠纪-侏罗纪界线附近古环境变化的主要驱动因素(Rigo *et al.*, 2020; Schoepfer *et al.*, 2022).北美阿拉斯加地区的Angayucham洋底火山的喷发被认为是诺利期Alaunian-Sevatian时期的气候与环境变化的主要驱动机制(图2)(Zaffani *et al.*, 2017; Jin *et al.*, 2022a, 2022b; Sato *et al.*, 2023).然而,最近的锇同位素研究表明,Angayucham大火成岩省喷发要晚于牙形石*Mockina bidentata*的首现,与W3极端高温时期存在明显的时间差别(Sato *et al.*, 2023).

需要指出的是,诺利期与瑞替期之交的Sr和Os同位素比值(Kuroda *et al.*, 2010; Callegaro *et al.*, 2012)表明CAMP的前火山活动可能接近诺利期极端温室阶段.然而近年来关于该岩浆作用的持续时间和空间仍有许多不同意见(Marzoli *et al.*, 1999, 2011, 2018; Tanner *et al.*, 2004; Davies *et al.*, 2017; Sato *et al.*, 2023).因此,CAMP事件或CAMP的前火山活动是否造成了诺利期极端温室事件还有待深入研究.

除此之外,至少有五次火流星撞击地面的构造(直径从9~85 km不等,撞击时间在235~200 Ma前; Clutson *et al.*, 2018)被发现于现在的北纬地区.其中最大的一次为Manicouagan小行星撞击事件(图2),发生在中-晚诺利期之交(Ramezani *et al.*, 2005; van Soest *et al.*, 2011),直径约85 km(Spray *et al.*, 2010),与诺利期极端温室事件时间上耦合,然而,目前尚不清楚这次撞击是否会对气候产生长期影响(Clutson *et al.*, 2018).

碳同位素在晚三叠世诺利期早期主要维持在较高值,并在早诺利期末期达到最大值(Early Norian Event, ENE),随后在诺利期极端温室时期,碳同位素逐渐开始负偏,并在中-晚诺利期之交,即全球海表水温达到35 °C时,碳同位素比值达到并维持在低值(Cramer and Jarvis, 2020)(图2).前人在西特提斯地区晚三叠世诺利期晚期,即诺利期极端温室事件之后的快速变冷阶段,发现数百万年内碳同位素维持在低值以外,同样出现数次快速负偏,并称之为"诺利期碳同位素混乱区间"(Whiteside and Ward, 2011).该事件随后在全球陆相及海相地层中均被报道(Preto *et al.*, 2013; Zaffani *et al.*, 2017; Jin *et al.*, 2022a, 2022b; Wu *et al.*, 2024),表明该事件可能是全球碳循环波动留下的记录.大火成岩省的喷发以及地外撞击等灾难性事件被解释为与该时期碳同位素快速波动有关(Rigo *et al.*, 2020; Sato *et al.*, 2023),然而目前关于以上事件与该时期碳同位素混乱事件之间的具体联系尚不清楚.

5　国内研究现状

由上可见,晚三叠世中晚诺利期至瑞替期早期发生了重要的生物灭绝和演替事件(双壳、菊石、放射虫、孢粉、牙形石、钙质超微化石、陆地脊椎动物等)和明显的古气候、古环境变化(大气pCO_2下降、碳同位素混乱区间、牙形石氧同位素负偏等),这些生物与气候环境的变化可能是三叠纪末生物大灭绝的序幕.上述研究显示关于诺利期极端温室期的研究已经成为了当今的热点之一.但是以上大部分研究区均在特提斯洋西部和联合古大陆赤道地区.

晚三叠世时我国南方位于东特提斯地区,与西特提斯地区受早基梅里运动影响不同,该地区在该时期主要受印支运动影响.印度支那、羌塘板块与华南板块正在汇聚(Golonka *et al.*, 2018; Huang *et al.*, 2018; Metcalfe, 2021; Yu *et al.*, 2022),板块构造活动活跃.许多地方也有同期的火成岩报道:如三江地区北段的松潘-甘孜褶皱带和义敦地体的晚三叠世岩浆岩事件(其形成年龄分别为约210 Ma前(Zhan *et al.*, 2018; Wang *et al.*, 2024)和216 Ma前(Zhan *et al.*, 2021));羌塘盆地的大规模火山与火山沉积事件(225~201 Ma; Wang *et al.*, 2008; Fu *et al.*, 2010; 付修根等, 2020);秦祁昆结合部的岩浆岩事件(225~205 Ma; 解小龙等, 2015);滇缅泰马地块(Sibumasu)岩浆岩事件等(230~200 Ma, Wang *et al.*, 2018及其中引用的文献),说明我国华南地区在诺利期同样处于板块构造、火成岩等事件活跃背景之下.

需要指出的是,尽管东特提斯地区在这一关键时期板块构造、火成岩等事件很活跃,但在印度支那、羌塘板块与华南板块(或其中的微板块)周缘的台地仍然形成了许多碳酸盐岩沉积,很好地保留了气候变化与海相生物演化的信息.前人在这一地区建立了比较好的海相生物地层格架(董致中和王伟, 2006; Du *et al.*, 2020; Zeng *et al.*, 2021, 2023等).近年来,我国华南地区有关该时期生物演化与环境事件的研究也越来越多,如Jin *et al.*(2022b)对云南保山地区的碳同位素研究认为,该时期的碳同位素偏移可能与Angayucham玄武岩侵位期间的脱气作用有关.Zeng *et al.*(2023)基于云南保山地区的牙形

石资料也报道了该时期牙形石动物群存在重要转变.Jia *et al*.(2024)报道了该时期钙质超微化石存在小型化现象,可能与极端温室事件相对应.Chen *et al*.(2024)基于牙形石氧同位素和锶同位素的研究更是证实了诺利期极端温室事件在东特提斯地区的存在,并认为该次温室事件之后的变冷是高温以及高湿度环境下的硅酸盐的快速风化,快速消耗大气中CO_2,从而导致全球气温及海洋表层温度的快速下降.

6 结论与展望

晚诺利期存在一个极端温室期,从中诺利期延续到晚诺利期早期,该时期低纬度地区海水表面最高温度可高达35 ℃,极高温期发生在牙形石 *Mockina bidentata* 带下部所代表的时限.诺利期极端温室期的干湿气候变化在不同地区表现不一致,其变化情况尚不完全清楚;诺利期极端温室期伴随着重要的生物演化事件,其与该时期地质事件及气候变化之间的因果联系也不清楚.我国发育有良好的诺利期地层序列,是东特提斯地区研究诺利期极端温室期气候变化与生物演化的理想区域.这些事件的全球意义、潜在因果关系以及在东特提斯的响应等亟需深入研究.

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