

光之于生命：早期地表光化学过程驱动 关键营养元素循环

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摘要: 太古宙是地球-生命协同演化的关键时期。营养元素的循环是连接固体地球和早期生物演化的关键纽带, 但早期迥异的地表环境特征深刻影响了营养元素的可获得性。本文主要围绕地球早期环境条件下的营养元素循环及生物可获得性前沿科学问题, 尤其关注一些在早期生物起源和演化中发挥关键作用的限制性营养元素, 综述了近年来有关早期光化学环境对关键营养元素循环的影响, 重点总结了地球系统多圈层相互作用下光化学驱动的早期营养元素循环在重大环境-生物演变事件中扮演的潜在角色, 最后展望了光化学影响行星系统宜居性演化方面的研究。

关键词: 太古宙; 营养元素; 光化学; 宜居性; 共演化

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Light to life: Photochemical processes drove the cycling of bio-essential nutrients on the early Earth

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Abstract: The Archean Eon witnessed the initiation of the co-evolution of geosphere and biosphere, which was potentially linked by the geochemical cycles of nutrient elements. However, the distinctive environmental conditions should have resulted in vastly different geochemical cycles of the nutrients and thus their availability on the early Earth. Here, we overview the current understanding of Archean geochemical cycles and availability of nutrients, especially those thought to limit the origin and productivity of early life. Particularly, we emphasize some recent advances on the large impacts of photochemistry in early nutrients' cycles and assess the potentially important roles of photogeochemistry in the co-evolution of environment and biology on the early Earth. At the end, we advocate for more attention to the role of photochemistry in planetary habitability, including the early Earth, Mars, and other planetary bodies.

Key words: Archean Eon; bio-essential nutrients; photochemistry; habitability; co-evolution

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0 引言

太古宙(距今40亿~25亿年前)是地球系统演化的关键时期。在这一时期,地表已经拥有了较为稳定且宜居的大气和海洋(Wilde et al., 2001; Valley, 2002),并且伴随着大陆成分的演化和出露(Flament et al., 2013; Tang et al., 2016; Korenaga et al., 2017; Bindeman et al., 2018),逐渐形成了现代类型的地球化学循环模式(Bindeman et al., 2018)。与此同时,生命在太古宙的早期出现并有了明确的化石证据(Alleon and Summons, 2019; Javaux, 2019),并且随后演化出多种多样的微生物代谢作用(Knoll and Nowak, 2017; Moore et al., 2017)。在太古宙末期,地球系统作用下产氧光合作用微生物的繁盛快速氧化了全球大气(Luo et al., 2016; Ward et al., 2016),即“大氧化事件”,为后来真核和多细胞生物的起源奠定了关键的环境基础(Mills et al., 2014)。总之,在这一横跨15亿年的地球少年期,诸多重大地质、环境及生命事件轮番上演,为地球-生命协同演化的壮丽篇章拉开了序幕。

虽然生命依赖固体地球,但从元素组成上来讲,生命却具有与固体地球迥异的化学特征。一个最鲜明的例子是,构成生命的6大必需元素C-H-O-N-S-P显著区别于构成地壳的6大主要元素O-Si-Al-Fe-Ca-Na(Rudnick and Gao, 2014)。这是由于生命需要依赖活跃的水-岩相互作用释放出固体岩石中的营养元素。这种关系体现在生命与地表水体具有相似的元素组成(Moore et al., 2013)。因此,地球系统作用下水化学环境特征,尤其是生命必需元素的可获得性,是连接固体地球和生命长时间尺度演变的关键纽带(Zerkle et al., 2005; Anbar, 2008; Dupont et al., 2010; Moore et al., 2017)。例如,人们普遍认为大陆风化和河流输入的活性磷是控制地球水体生产力的关键限制性营养元素之一(Tyrrell, 1999)。此外,地球历史时期海水中钼、镍等构成生物酶活性中心的过渡金属元素的可获得性也被认为是推动多种微生物代谢起源和演化的重要环境因素(Zerkle et al., 2005; Dupont et al., 2010)。

地表水体中生命必需营养元素的可获得性主要取决于温压、氧化还原等环境条件。在太古宙整体无氧条件下,高辐射通量的紫外线可以直射地表(Cnossen et al., 2007; Farquhar et al., 2014),诱发广泛的光化学反应,例如,有机物的光化学合成(Pearce et al., 2022; Zang et al., 2022)和转化(Trainer et al., 2006; Farr et al., 2023),以及早期地表丰富的还原性物质的无氧光化学氧化过程等(Cairns-Smith et al., 1978; Kim et al., 2013; Liu et al., 2020; Ritson et al., 2020;

Hao et al., 2022),深刻影响了早期地表的宜居性及生命的起源和演化。本文主要围绕太古宙这一地球-生命协同演化的关键时期,总结早期地表环境对部分生命必需营养元素的可获得性的影响,重点关注近年来关注较多的地球表面的光化学过程,并对这一新兴交叉方向的关键科学问题和潜在发展方向进行展望。

1 早期海洋中的关键营养元素

太古宙早期具有广袤的海洋环境和有限出露的陆地(Korenaga, 2021; Tang et al., 2024),因此,早期生命很有可能主要栖息在海洋环境中(图1)。目前,比较公认的最早生命化石证据出现在38亿年前(Mojzsis et al., 1996)。此外,诸多的证据显示,早期生命在太古宙中期已经演化出多种多样的代谢作用,包括产甲烷作用、固氮作用、铁氧化/还原作用及产氧光合作用等(Moore et al., 2017; Knoll and Nowak, 2017)。但是,相比于现代,早期生态系统的组成还较为单一,以单细胞原核生物为主(Knoll and Nowak, 2017),电子传输系统也比较简单(Knoll et al., 2016),对环境的依赖性更强。在诸多影响生命的环境条件中,营养元素的可获得性往往限制了生物种群的总体规模(Hao et al., 2024),尤其是部分环境中相对比较缺乏的营养元素,例如现代地表水体中的磷和氮(Falkowski, 1997; Tyrrell, 1999)以及广阔海洋中的铁(Behrenfeld et al., 1996),被称为“限制性营养元素”。

类似于现代,磷也被认为是限制太古宙时期生物规模的关键限制性营养元素之一(Bjerrum and Canfield, 2002; Jones et al., 2015; Hao et al., 2020a)。但是,它在太古宙时期的地球化学行为与现代大不相同。例如,地表水体中的磷依赖大陆风化和河流输送(Ruttenberg, 2014),但大陆在太古宙中晚期才开始大规模出露于海平面之上(Flament et al., 2013; Korenaga et al., 2017; Tang et al., 2024)(图1),限制了它在太古宙早期和中期的输送规模(Hao et al., 2020b)。此外,太古宙整体富Fe(II)的水体在多种生物或非生物作用下可以发生无氧氧化(Cairns-Smith, 1978; Konhauser et al., 2007),沉淀了大量的富Fe次生矿物,如Fe(III)氢氧化物、绿锈及铁蛇纹石等(Cairns-Smith, 1978; Tosca et al., 2016; Halevy et al., 2017),甚至形成大规模的条带状铁建造(Banded Iron Formations或BIFs)(Bekker et al., 2014)。这些矿物可以高效地吸附和沉淀水体中的溶解磷,从而降低海水中生物可利用磷的水平(Bjerrum and Canfield, 2002)。太古宙时期整体无氧的地表环境还会影响有机磷在海水中的再循环效率,从而进一步降低海洋中的磷含量和循环通量(Kipp

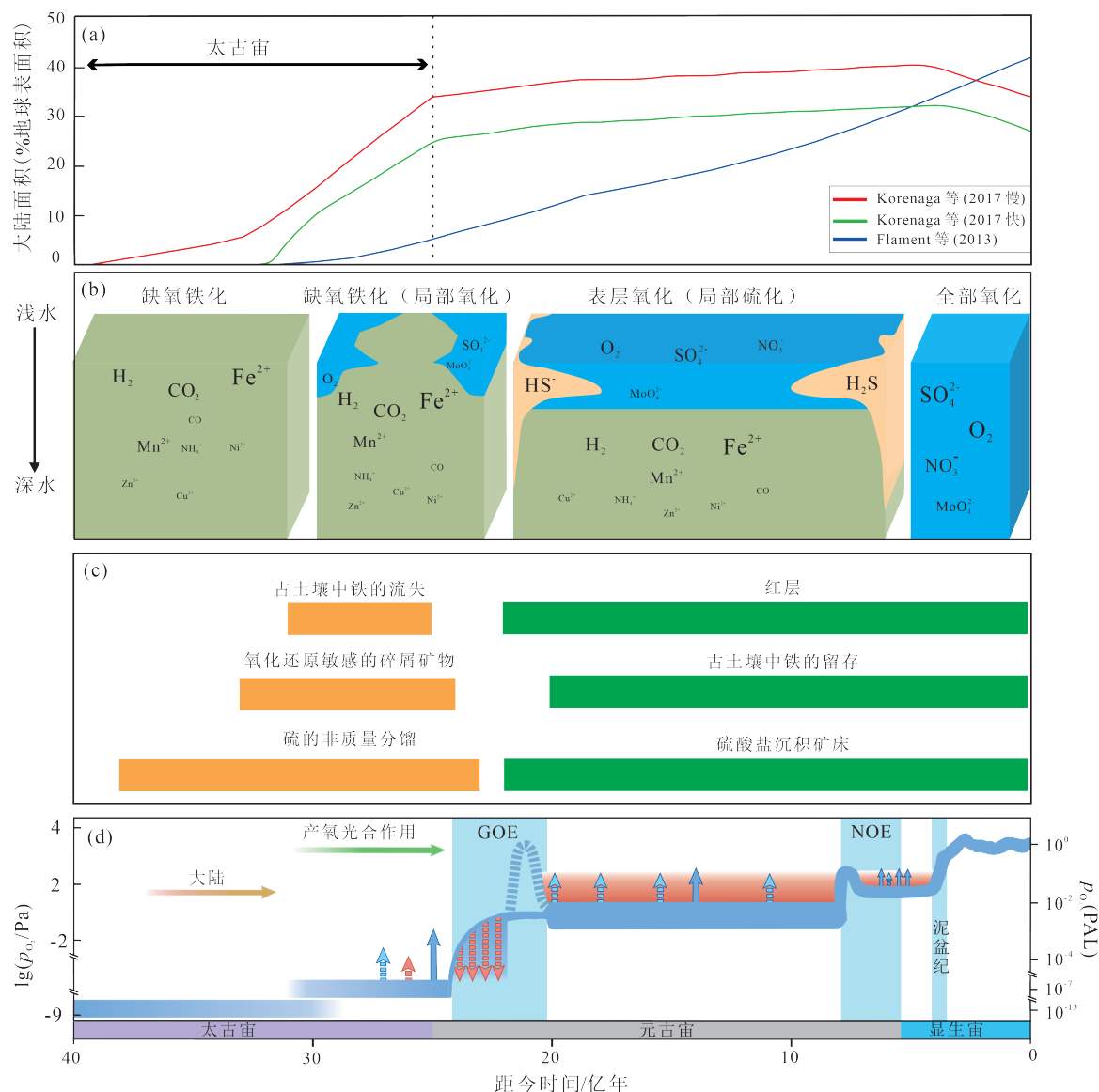


图1 地表环境长时间尺度演化历史。(a)陆地出露面积演变历史;(b)海洋氧化还原状态及海水化学演变历史(Poulton and Canfield, 2011; Moore et al., 2017);(c)早期地表风化及海洋沉积记录演变历史(Ward et al., 2016);(d)大气中氧气含量演变历史(Lyons et al., 2024)

Fig. 1 Evolution of the surface environments during the geological history. (a) Evolution history of land emergence (Flament et al., 2013; Korenaga et al., 2017); (b) evolution history of ocean redox state and water chemistry (Poulton and Canfield, 2011; Moore et al., 2017); (c) evolution history of continental weathering and marine sedimentary records (Ward et al., 2016); (d) evolution history of atmospheric $p_{O_2, (g)}$ (Lyons et al., 2024)

and Stueken, 2017)。总体上看,太古宙时期海洋中磷的生物可利用性可能比现在要低(Hao et al., 2024), 主要体现为海洋沉积物普遍是低磷的(Planavsky et al., 2010; Reinhard et al., 2017)。不过,也有学者提出早期无氧水体中洋壳风化可能也会释放部分磷供给早期生命(Syverson et al., 2021),但是最近的一些吸附实验对这个假说提出了挑战(Cui et al., 2024)。

除了磷,一些生命必需的金属元素,包括Fe、Mo、Cu等,也被认为是限制太古宙时期生物规模或影响生

物代谢演化的关键营养元素(Zerkle et al., 2005; Dupont et al., 2010; Moore et al., 2017)。例如,虽然早期水体普遍呈现铁化的特征(Poulton and Canfield, 2011),但当时可能大规模发生的不产氧光合作用会消耗大量的Fe(II)作为电子供体(Swanner et al., 2020), 导致整体生物量受控于总的Fe(II)等还原性物质的供给通量(Ward et al., 2019)。此外,Fe、Mo、Cu等过渡金属元素具有灵活的变价特征,构成了固氮酶等生物酶的活性中心(Da Silva and Robert Williams, 2001)。

在自然界中, Mo、Cu等微量金属往往富集在金属硫化物中(Kendall, 2021), 需要依赖硫化物的氧化性风化被释放到水体中, 供给生物利用(Zerkle et al., 2005)。然而, 早期无氧的地表环境会极大地减慢硫化物的氧化性风化(Johnson et al., 2014), 并且降低这些金属离子在水体中的溶解度(Kendall, 2021)(图1)。因此, 早期水体中可能普遍缺乏生物可利用的Mo、Cu等过渡金属离子, 限制了部分生物代谢类型的演化和规模(Zerkle et al., 2005; Anbar and Holland, 2008; Moore et al., 2017)。

上述对于太古宙营养元素循环的总体认识主要是基于无氧条件下气-水-岩相互作用的基本规律。但是, 近年来越来越多的研究表明, 一些局部或者高能过程可能会极大地影响太古宙时期限制性营养元素的可获得性和循环特征, 如陨石输运假说(Pasek and Paur-etta, 2008)、氧隙流假说(Whiffs of Oxygen)(Anbar et al., 2007)、陆地产氧光合作用生物席假说(Microbial Mat)(Lalonde and Konhauser, 2015)、矿物摩擦产氧假说(He et al., 2021)等。本文主要探讨近些年关注较多的无氧条件下光化学过程在早期营养元素循环中的作用, 重点关注磷和过渡金属元素这些潜在的限制性营养元素。

2 早期地表光化学环境

太阳光提供了当前地表接收到的绝大部分(>95%)能量(Trenberth et al., 2009)。不同于现代, 太古宙时期更年轻的太阳具有较小的半径, 其亮度比现在太阳要弱15%~30%(Gough, 1981; Bahcall et al., 2001)。同时学界普遍认为早期地幔具有更高的温度(Cawood et al., 2022), 导致地表会发生更为强烈且频繁的火山活动(Isley, 1995)。因此, 早期地表的能量收支结构可能不同于现代, 地热所占比重相对更为重要。不过, 虽然太阳的总体亮度较弱, 但早期太阳出射光谱中高能的部分要远强于现代(图2), 具体体现在X线、紫外等较短辐射(Spencer, 2019)。这些波段的光子具有较高的能量, 可以驱动广泛的行星表面化学过程, 影响早期地球及其他星体的宜居性演化(Falkowski, 2015)。

太阳入射光谱在到达地面时会受到行星大气组分的强烈吸收, 导致地表接收的光谱变窄且强度减弱。例如, 地球大气中的水汽和CO₂可以强烈地吸收200 nm以内波段的紫外光和其他高能射线(Ranjan and Sasselov, 2016)。此外, 现代大气中的臭氧层会强烈吸收200~300 nm波段的紫外线(Matsumi and Kawasaki, 2003), 为地表生物营造一个健康的辐射环境。但是, 太

古宙时期大气普遍呈现出低氧($p_{O_2} < 10^{-8}$ MPa)且弱还原性($p_{H_2} > 10^{-6}$ MPa)的特征(Hao et al., 2019; Catling and Zahnle, 2020), 导致大气光化学反应无法产生显著的臭氧及臭氧层(Cooke et al., 2022)(图1、2)。在这种大气环境下, 200~400 nm的大部分紫外线可以直射地表(Cnossen et al., 2007)(图3), 诱发地面物质发生广泛的光化学反应, 例如著名的硫同位素的非质量分馏(Farquhar et al., 2000)。

除了氧气, 大气中的其他成分也可以影响早期地表的光化学环境。例如, 蛇纹石化作用和产甲烷作用微生物可以释放一定的甲烷(Kral et al., 1998; Etiope and Sherwood-Lollar, 2013), 并在早期无氧大气中积累(Zahnle et al., 2006)(图2)。这些甲烷在早期紫外线的作用下, 会发生一系列光化学反应, 甚至可能形成有机霾(Pavlov et al., 2001; Trainer et al., 2006), 从而有效阻隔部分紫外线到达地表(Arney et al., 2016)。碳、硫等同位素等证据也指示, 太古宙中晚期可能发生过持续性或间歇性的“有机霾”事件(Domagal-Goldman et al., 2008; Izon et al., 2015)。但是, 目前对于太古宙大气中甲烷的含量等控制有机霾产生的环境因素, 以及有机霾产生过程和机制的认识还主要依赖理论模型或实验室模拟, 缺乏确凿的地质记录, 因而限制了更精确的当时地表光化学环境的重建, 尤其是紫外环境。

3 光化学过程在早期营养元素循环中的作用

在全球尺度上, 海洋中的营养元素可获得性主要受控于大陆输送和海洋循环两个主要过程。地表条件下, 太阳光可以入射的深度(即透光层, photic zone)恰恰是大陆和海洋中发生活跃气-水-岩-生物相互作用的界面。其中, 紫外线和可见光在岩石中的穿透性较差, 一般小于毫米级(Carrier et al., 2019), 但在大气和水体中的穿透性较好, 可以穿透深达几米至几十米的清澈水体(Tedetti and Sempéré, 2006)。不同物质具有不同的吸收光谱特征和吸光度(图3)。此外, 物质本身的光学带隙(band gap)结构决定了光化学反应的能否发生: 对应带隙能量的特定频率的光子会被吸收并激发电子发生跃迁, 导致光化学反应的发生(Evans et al., 2013)。

对于一些N、S等常见气态元素, 火山喷发和大气传输是重要的地表循环途径(Galloway, 2014; Brimblecombe, 2014)。在太古宙时期, 核-幔分异及地幔自氧化等过程基本完成(Rubie et al., 2015), 地幔的氧逸度已经升高到接近现在水平(Trail et al., 2011)。在这种情况下, 火山喷出的C、N和S等变价气态元素主要以其氧化态或中性态为主, 包括CO₂、N₂和H₂S-SO₂混合

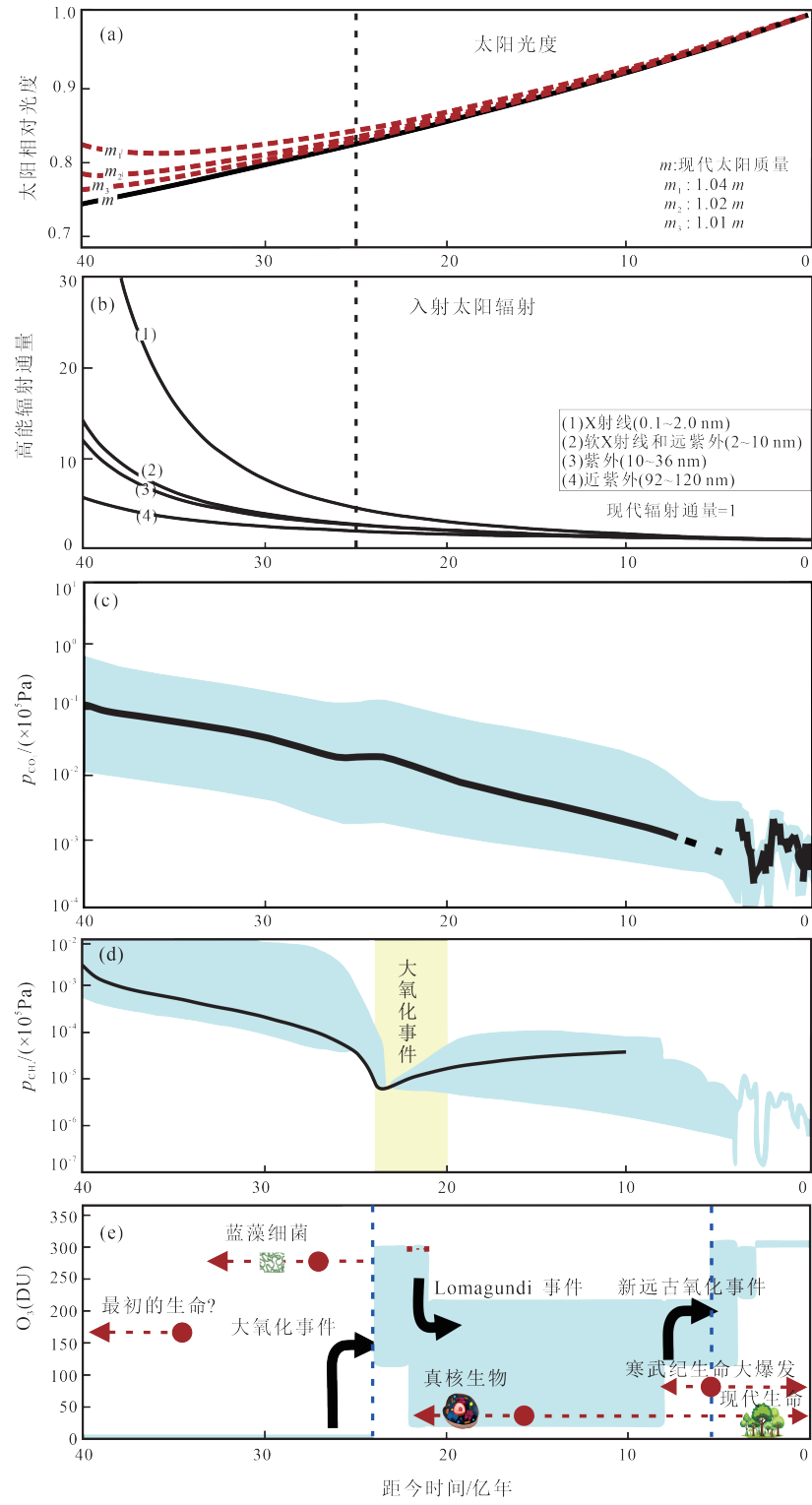


图2 早期地表光化学环境的演变规律及其控制因素。(a)地表接收到的太阳光度演变历史(Gough et al.,1998; Spencer,2019);(b)地球接收到的入射太阳高能辐射强度变化历史(Spencer,2019);(c)地表大气中CO₂分压的演变历史(Catling and Zahnle,2020);(d)地表大气中CH₄的分压演变历史(Catling and Zahnle,2020);(e)地表大气中臭氧含量的演变历史(Cooke et al.,2022)

Fig. 2 Evolution of the photo-environment and its controlling factors. (a) Total solar luminosity received by the Earth (Gough et al.,1998;Spencer,2019);(b) incident solar radiation of high-energy (Spencer,2019);(c) evolution history of atmospheric CO₂ (Catling and Zahnle,2020);(d) evolution history of atmospheric CH₄ (Catling and Zahnle,2020);(e) evolution history of atmospheric ozone (Cooke et al.,2022)

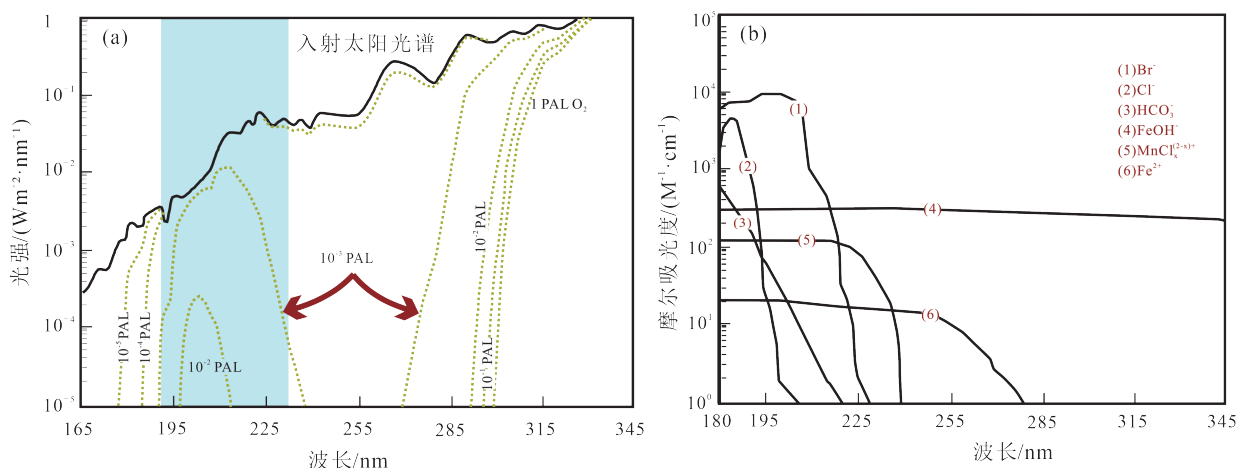


图3 (a)不同大气氧含量情况下,地表接收到的紫外辐射波长分布(Farquhar,2014);(b)早期海水中主要离子的摩尔吸光度(Anbar and Holland,1992)

Fig. 3 (a) UV radiation received on the Earth surface as a function of atmospheric O₂ level (Farquhar,2014); (b) molar absorbance of major dissolved species in the early seawater (Anbar and Holland,1992)

气(Kasting et al.,1993),构成了太古宙大气中主要的气体成分(Catling and Zahnle,2020)。相对来说,CH₄和NH₃等还原性气体在火山去气中含量较低,且在大气中容易发生光解(Kasting,1982;Kasting et al.,1983),难以积累到很高浓度。但是,富含超基性和基性岩石的早期洋壳的风化过程,尤其是热液活动,可以释放氢气(Sherwood-Lollar et al.,2014),诱发广泛的还原反应。此外,早期比较频繁的撞击过程,可以在撞击坑附近引发广泛的热液活动,释放还原性气体(Zahnle et al.,2020)。这些还原性气体在早期光化学的作用下,可以产生HCN和有机氮等早期生命可利用的形式(Pearce et al.,2022;Zang et al.,2022)。此外,早期大气中的N₂在强紫外线的作用下,还可以被光化学氧化,生成微量的NO_x,供给早期生命(Kasting and Ackerman,1985;Wong et al.,2017)。而大气中H₂S和SO₂的无氧光化学氧化会部分产生S_x等单质形式(Pavlov and Kasting,2002;Harman et al. 2018),不利于早期生命的摄取。

对于大部分营养元素,大陆风化和河流输送是海洋中生物可利用营养元素的最主要来源。太古宙时期地表整体无氧的特征会抑制地表的氧化性风化,有利于Fe(II)、Mn(II)等的释放(Hao et al.,2017a and 2017b;Rye and Holland,1998),但不利于硫化物等的溶解(Johnson et al.,2014)(图1),从而导致大陆Fe(III)、MnO_x和硫酸盐等氧化性物质及富集在金属硫化物中的过渡金属元素(包括Mo、Cu、Zn等)输入通量的降低(Hao et al.,2024)。即使如此,在无氧条件下Fe²⁺、Mn²⁺、FeCO₃、MnCO₃、FeS₂等常见还原性物质也都会被200~400 nm的紫外线激发(图3),发生光化

学氧化,生成Fe(III)、Mn(III)、SO₄²⁻等(Anbar and Holland,1992;Xu and Schoonen,2000)。这个过程可能广泛发生于早期岩石的表面或河流的浅层,并且伴随着H₂的释放(Cairns-Smith et al.,1978;Kim et al.,2013;Liu et al.,2020;Hao et al.,2022)。随着太古宙中后期大陆的大规模出露,还原性物质的光化学氧化可能为早期海洋生命提供了紧缺的氧化性物质和营养元素(Liu et al.,2020;Hao et al.,2022),有利于大氧化事件的发生,也为解释地层中记录的太古宙氧化性风化信号提供了新机制(图1、4)。

营养元素通过河流输入到海洋后,会被海洋生物快速摄取利用,因此,表层海水中营养元素含量往往很低(Millero,2013)。随着浮游生物的死亡,有机质的沉降和降解会在次表层海水中优先释放部分营养元素,供给海洋生命(Schlesinger,1998)。在现代氧化性海水中,这种内循环过程贡献了超过95%的生物初级生产力所需的磷等营养元素(Schlesinger,1998)。但是,太古宙时期整体厌氧的水体特征以及相对简单的生态系统组成可能会导致再循环速率极其低下(Kipp and Stüeken et al.,2017)。此外,海水中溶解的Fe(II)和Mn(II)可以发生不同程度的光化学氧化(Cairns-Smith et al.,1978),生成Fe(III)/Mn(III)-氢氧化合物等氧化物(Anbar and Holland,1992;Konhauser et al.,2007)(图4),可以显著吸附且沉淀海水中的溶解磷等营养元素(Bjerrum and Canfield,2002;Jones et al.,2015)。近期,Farr等(2023)通过光化学模拟实验,发现海洋中常见的小分子有机磷可以在模拟早期海洋表面环境条件下发生光化学氧化,释放磷酸根,据此提出了光化学驱动的早期海洋营养元素再循环的假说。此

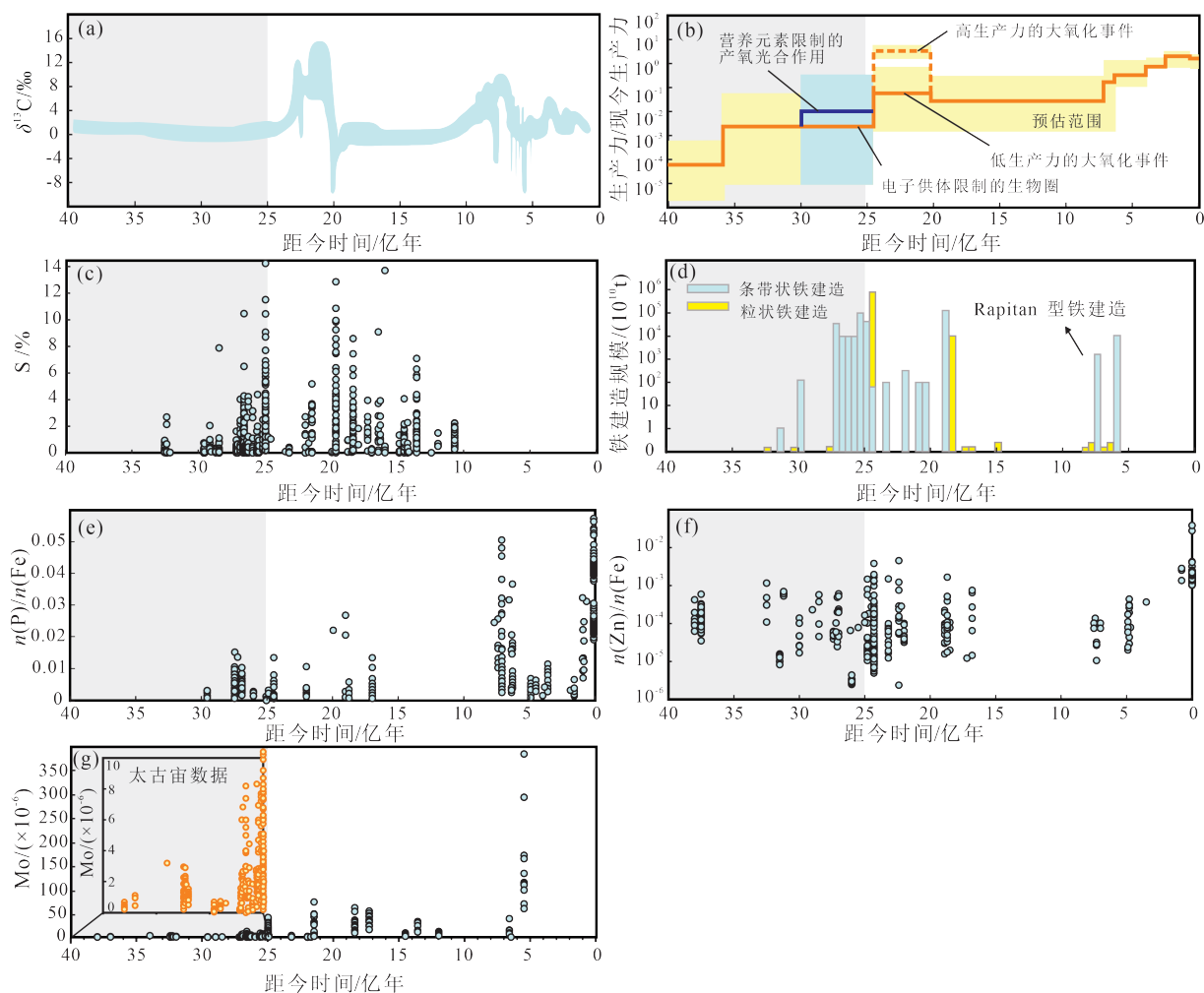


图4 地质历史上不断演变的生物地球化学循环的沉积记录。(a)地质历史上海洋碳酸盐的碳同位素(Lyons et al., 2014); (b) 海洋初级生产力的重建演化历史(Crockford et al., 2023); (c)地质历史上页岩中的硫含量(Stüeken et al., 2012); (d)地质历史上铁建造的产出记录(Bekker et al., 2010); (e)条带状铁建造中的磷/铁摩尔比(Robbins et al., 2016); (f)条带状铁建造的锌/铁摩尔比(Robbins et al., 2013); (g)地质历史上页岩中的钼含量(Stüeken et al., 2012; Reinhard et al., 2013)

Fig. 4 Sedimentary records of evolving biogeochemical cycles during the geological history. (a) C isotopes of marine carbonates through Earth's history (Lyons et al., 2014); (b) reconstructed evolution history of primary productivity in the ocean (Crockford et al., 2023); (c) S content in shale (Stüeken et al., 2012); (d) occurrence of Iron Formations in geological history (Bekker et al., 2010); (e) P/Fe molar ratio in Banded Iron Formations (Robbins et al., 2016); (f) Zn/Fe molar ratio in Banded Iron Formations (Robbins et al., 2013); (g) Mo content in shale (Stüeken et al., 2012; Reinhard et al., 2013)

外,有研究表明,陨石输入的 PO_3^{3-} 等还原态磷也可以在无氧条件下发生光化学氧化,生成磷酸根,以供给早期生命(Ritson et al., 2020)。

综上所述,早期地球强烈的紫外线照射等辐射环境可能深刻影响着N、P、S和过渡金属等限制性营养元素的循环过程和生物可利用性。不过,通过梳理前人的研究,我们也认识到目前有关光化学影响早期地球营养元素循环的研究涵盖的地球化学循环过程还较为单一,体系相对较简单,未来亟需立足于地球系统的思维来更全面地衡量光化学的潜在重要贡献。此外,本

文主要针对200~400 nm波段的紫外线进行了探讨,并未涉及更高能量的太阳辐射(包括X射线、Gamma射线及带电粒子等)。虽然这些更高能的辐射很难直接到达早期地表(Cnosson et al., 2007),但他们也可能诱发大气中一些气态营养元素的高能反应(Airapetian et al., 2016; 2020),进而间接影响早期营养元素循环。

4 总结及展望

本文简要介绍了光化学反应可能在早期地表营养元素循环中发挥的潜在作用,尤其是前人认为的一

些限制性营养元素。在系统评估光化学反应对早期宜居性的意义时,我们需要关注时间和空间两个方面的演变规律,尤其是大陆出露等一些重大地质过程可能深刻影响光化学反应对营养元素循环的贡献。例如,随着太古宙中晚期大陆的抬升,富含还原性矿物的陆地得以暴露在海平面以上,有利于矿物等的无氧光化学氧化,释放限制性营养元素(Hao et al., 2022)。与此同时,河流输入的营养元素有利于微生物在早期河口或浅海的繁盛,尤其是产氧光合作用生物(Hao et al., 2020b),也为光化学有效驱动海洋有机物再循环创造了条件(Liu et al., 2020)。这些作用的叠加可能会放大太古宙晚期大陆出露对地表生物的影响,尤其是为产氧光合作用的兴起和大氧化事件的发生创造有利条件(Hao et al., 2020a; 2022)(图4)。

在大氧化事件之后,光在早期生物地球化学循环中的角色发生了根本性的转变:一方面是臭氧层的建立使得到达地表的紫外线等高能辐射强度锐减(Wo-gan et al., 2022)(图1~3);另外一方面,产氧光合作用开始在整个生态系统中占据主导地位,直到现在(Crockford et al., 2023)。此后,光主要以一种我们熟知的更直接且规模更大的方式影响着元素循环,即产氧光合作用。不过,我们需要注意,即使在大氧化事件后的元古宙(24亿~5.4亿年前),大气中的氧气及臭氧水平依然没有达到现在水平(Lyons et al., 2021)(图1、2),部分200~400 nm波段的高能紫外辐射依然可以到达地表(Farquhar, 2014)(图3),依然可以诱发一些地表物质的光化学反应,也会威胁早期生命的繁盛。

除了地球之外,一些地外潜在宜居星体在演化早期或现在也会发生广泛的光化学反应。例如,早期火星虽然可能拥有类似现代地球的较为浓密和稳定的大气(McElroy et al., 1977; Jakosky et al., 2017),但是当时的大气组成被认为至少存在间歇性还原的特征(Catling and Kasting, 2017; Wordsworth et al., 2021),类似于上述我们讨论的太古宙时期地球的环境。在这种环境条件下,紫外线也可以诱发地表物质发生广泛的光化学反应(Cockell et al., 2000; Batalha et al., 2015)。随着火星大气的显著逃逸,火星逐渐演化出类似于现代的稀薄氧化性大气特征(Catling and Kasting, 2017)。与此同时,火星的磁场被认为存在的时间也比地球要短且强度较弱(Mittelholz et al., 2020; Steele et al., 2023)。在这种情况下,小于400 nm波段的紫外线等高能辐射以及太阳风带电粒子会极大地影响火星地表环境(Lammer et al., 2013),诱发广泛地光化学反应(McElroy et al., 1977),塑造了我们观察到的“红”色(氧化性)特征。对于这些星体的进一步研究将

为揭示光化学反应如何影响行星宜居性提供重要的参考。

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·亮点速读·

碳酸岩熔岩与现代金星大气形成的关系

金星与地球同处于宜居带内,是地球的姐妹星。它有着太阳系类地行星中最浓厚的大气层,大气压力是地球的92倍,其中96%以上是CO₂。强烈的温室效应使金星表面的平均温度高达462℃,在近赤道的洼地甚至高达500℃,比最靠近太阳的水星还要热,是太阳系中最热的行星。在2020年,科学家在金星大气层中侦测到磷化氢的存在,显示金星可能曾有过生命活动。同时,气候模拟也表明金星可能经历了约30亿年有过液态水的、适合生命生存的温和气候阶段,但最终被强烈的温室效应所终结。金星当前的极端环境与其大气中稠密的CO₂有密切的关系,据估算其大气中的碳含量几乎等于地球岩石圈和大气圈中碳含量的总和。对于金星大气中巨量碳的来源,以往的研究认为可能是由大火成岩省的去气作用所导致的。然而金星的地表岩石主要形成在2.5亿年前后,难以解释金星长期存在的高浓度大气CO₂。而地球上的大火成岩省主要以镁铁质岩石为主,除非岩浆的总量超过地壳,否则仅凭大火成岩省的铁镁质岩浆活动并不足以产生金星高CO₂浓度大气。为此,一些研究者提出金星当前的大气可能继承自其早期阶段并一直延续至今。如果这一假说成立,则排除了金星曾存在过

长期宜居环境的可能性。

金星表面保留着一些不同岩浆和喷发类型的火山机构,表明非镁铁质岩浆可能参与了金星大气的形成。麦哲伦雷达影像显示金星平原上发育一种类似运河的“河道”,最长超过6800 km,是太阳系中最长的河渠系统。与在月球和金星上发现的另一种火山通道——蜿蜒月溪不同,运河状河道没有明显的源区,而且可能比蜿蜒月溪更长和/或更古老。由于金星表面极端的温度条件,液态水无法存在,因此有假说认为这些长运河是由碳酸岩、科马提岩和拉斑玄武岩等低黏度熔岩侵蚀形成的。近年来,机械热侵蚀作用在地球、月球、火星以及木卫1等行星的研究中都已经得到证实,而且认为仅碳酸岩等低温熔岩才能对金星表面产生机械热侵蚀。这暗示,相较于拉斑玄武岩和科马提岩,碳酸岩更可能是形成运河状河道的熔岩类型。同时,一些研究表明玄武岩和科马提岩的冷却速率太快,而拉斑玄武岩有限的喷发速率和熔岩流厚度也很难通过机械热侵蚀作用形成如此长的河道。为此,基于金星上存在裂谷带和富含CO₂的地幔,之前的研究倾向于认为碳酸岩熔岩可能更为普遍且更具优势。然而,目前尚无研究能够证明此类熔岩可以侵蚀

形成观测到的运河深度与长度。

针对这一问题,以亚利桑那大学Allyson R. Trussell为首的一个研究团队利用麦哲伦的雷达影像与高程数据,对金星上70条运河进行了测绘,并采用河道形成模型,反演了侵蚀出现观测截面规模的运河所需的熔岩体积,进而采用一维正演模拟方法确定能够重现运河横截面积与长度的熔岩流厚度及喷涌速率。模拟结果证实了碳酸岩熔岩具有形成此类运河所需的独特性质,同时表明这些碳酸岩的喷发可能释放了与金星现代大气总质量相当的CO₂。这一发现为金星大气的形成机制问题提供了可能的答案。金星曾长期存在宜居环境的可能性意味着,并非所有处于“金星带”内的系外行星都是炽热的荒芜之地。尽管恒星演化最终可能导致围绕类太阳恒星近距离公转的行星走向消亡,但在其存在的相当长时期内,这些行星表面仍有可能存在液态水海洋,具备维持长期宜居环境的潜力。

以上成果发表在:Trussell A R, O'Rourke J G, Williams D A, Flynn I T W, Black B A, Borrelli M E. 2025. The importance of carbonate lavas in outgassing Venus' modern-day atmosphere. *Science Advances*, 11: eadw1621

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