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新元古代重大地质事件及其与生物演化的耦合关系

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摘　要　新元古代的地球表层系统经历了超大陆裂解与重组、大规模冰期、古海洋氧化、埃迪卡拉生物群辐射与灭绝、后生动物兴起等一系列重大变革,这些地质事件与生物演化在时空上的耦合关系长期受多学科交叉研究领域的广泛关注。Rodinia超大陆的裂解伴随有超级地幔柱活动、古地磁真极移等复杂响应,裂解过程影响了大气圈和水圈中氧气和二氧化碳的循环,并可能直接导致了新元古代极端的气候条件。构造格局的变动对生物的影响主要体现在物质来源和生存环境的改变上,强上升洋流和强地表径流区域的富营养化促使生物大量繁盛。“雪球地球”期间巨大的选择压力为生物的多样化演变提供了可能,而其后冰川的快速消融则促进了生产力的爆发式增长及多种沉积矿产的形成。与此同时,大气—海洋氧气含量的增加和海水化学结构的改变使得多项元素及同位素指标发生了地质历史上最大幅度的波动,这种特殊的地质背景可能最终对生物演化产生了极为深刻的影响。

关键词　新元古代;超大陆事件;冰期事件;大气氧含量;生物演化

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0　引言

新元古代氧化事件前后一直被认为是地质历史中的关键转折时期,是地表环境从低氧到富氧、生物种群从原核类到疑源类再到真核类的进化辐射期,也是几次全球性冰川的形成—消融期和超大陆的裂解—重组期,多项地球化学指标随之发生了显著波动[1-5]。其实,地球的演化进程包括了若干次超大陆裂解—重组和冰期—间冰期旋回[6],这些地质事件往往与大气和海洋的氧化程度,以及生物演化极具耦合性(图1)。超大陆和冰期旋回控制了海平面升降和生物生存空间,而生物与地表环境的相互作用又进一步影响了大气圈、水圈的物质循环。对于在地球演化过程中表现最为特征的生物相,真核生物出现、真核藻类停滞性发育、后生动物出现、埃迪卡拉生物出现并灭绝、寒武纪生物大爆发及进入显生宙后的数次生物灭绝和复苏,均被认为与古海洋化学条件的改变、冰期及超大陆事件密切相关[11-14]。在我国华南、塔里木等地,新元古代地层包含多套黑色岩系,它们不仅是优质烃源岩层,而且伴生有多种金属、非金属矿产,具重要经济价值[15-16]。

前人对这一时期的古构造、古海洋及古生物等方面已开展了大量有益的工作[6,17-19],但由于涉及内容的广泛性及多学科交叉研究的复杂性,这些地质事件之间的相互关系及其控制因素等许多问题仍未得到圆满的解决。为此,本文力图从地球系统科学的角度出发,对新元古代重大地质事件和生物演化进程做一综述性评论,探讨各要素之间的耦合机制,为地球科学综合性研究的开展起到抛砖引玉的作用。

1　地质事件

地球的表层系统在新元古代发生过剧烈变化,包括超大陆裂解与重组、极端气候条件、古海洋氧化还原环境的改变等。这些重大地质事件之间存在着一定程度的联系,同时又可能影响了生物演化的进程。

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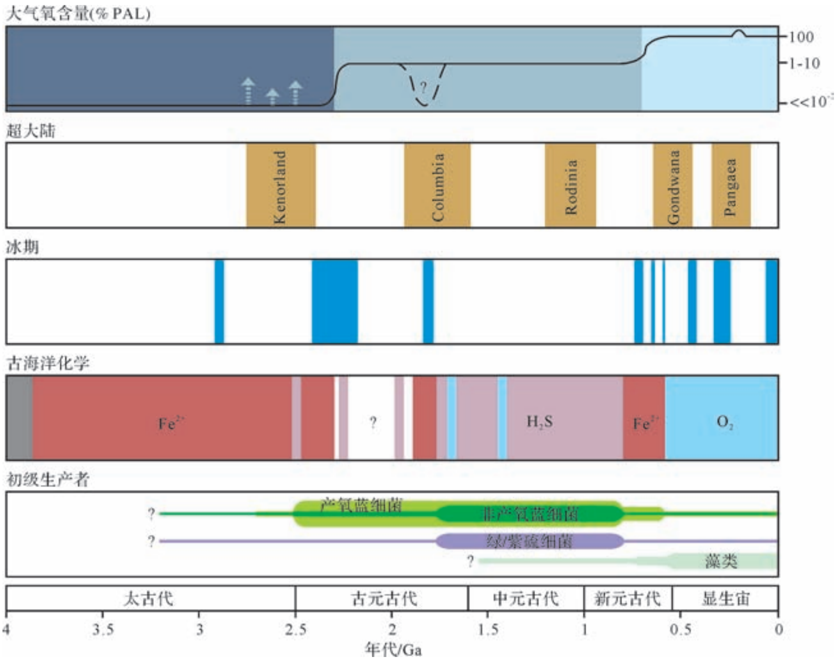

图1 地质历史时期的大气氧含量[7]、超大陆[4]、冰期[6]、古海洋化学[8-9]及初级生产者[10]

Fig.1 Temporal trends of atmospheric O_2 content[7], supercontinent formation[4], glaciations[6], deep ocean chemistry[8-9] and primary producers[10]

1.1 超大陆事件

1 300~900 Ma期间，地球上曾存在一个包括了当时几乎所有陆块的超级联合古陆，称之为Rodinia超大陆，其范围从赤道一直延伸到极地地区(图2)。印度东高止山脉带990~900 Ma的高级变质岩区[21]及我国华南920~880 Ma的弧火山岩和蛇绿岩仰冲侵位[20]均记录了Rodinia超大陆的汇聚过程，即格林维尔造山运动。其后，870 Ma和845 Ma的双峰式侵入岩体代表了Rodinia裂解作用的开始[22-24]。广泛的地幔柱活动主要发生在825 Ma和780~750 Ma两个阶段，证据包括：基性岩浆群[24-27]、高温科马提质玄武岩[28]、区域性穹窿[25]、以及大陆裂谷[29]等。大约780 Ma之后，Rodinia的主体已基本位于中低纬度地区，Li *et al.*[30]用真极移理论解释了这种板块位置的快速变化，并认为非赤道地区超级地幔柱的形成使得地球核幔边界以上的硅酸盐岩壳围绕格陵兰附近的旋转轴发生了近90°旋转。该理论随后在斯瓦尔巴特群岛东部[31]及澳大利亚[32]等地相继得到证实。

Rodinia超大陆解体后，在南半球地体重组形成了影响整个古生代的Gondwana超大陆(图2)。其中，西Gondwana在650~600 Ma时已初具规模，而东Gondwana的汇聚主要发生在750~620 Ma和570~500 Ma[33-35]。随着Mozambique洋的闭合，Gondwana超大陆得以最终形成，东西Gondwana相互聚合形成的一系列巨大山链可能代表了地球有史以来最大的一次陆陆碰撞[36]。

1.2 冰期事件

新元古代中晚期，地表气候变化剧烈，以几次大规模冰川的形成和消融为特征(图3)。成冰纪Sturtian冰期(720 Ma)[38,42]和Marinoan冰期(635 Ma)[44-45]均表现出全球性低纬度冰川的分布特点，而发生于约750 Ma的Kaigas冰期和580 Ma的Gaskiers冰期由于沉积物厚度不稳定且侧向连续性差，因此只代表区域性冰川事件[43,46-48]。

“雪球地球”假说最早由Kirschvink[49]提出，Rodinia超大陆在低纬度的裂解被认为是导致其形成的关键因素，尤其720 Ma劳伦古陆北部Franklin大火成岩省的喷发使大量铁镁质岩石在赤道地区遭受强烈风化[50]，其对CO_2的消耗可能是触发“雪球地球”的扳机[51]。Shen *et al.*[52]认为，新元古代中晚期之后臼齿碳酸盐岩的消失说明温室气体甲烷的释放量也发生明显下降。海洋初级生产力的增加对应着冰期前$\delta^{13}C_{carb}$的正漂，生物对碳的固定同样利于大气中的CO_2的消耗[53]。此外，由于冰盖相对于陆地和海水具有更高的反射率，两极冰盖扩张过程中，反射率变化所产生的正反馈效应很可能使地球在短时间内

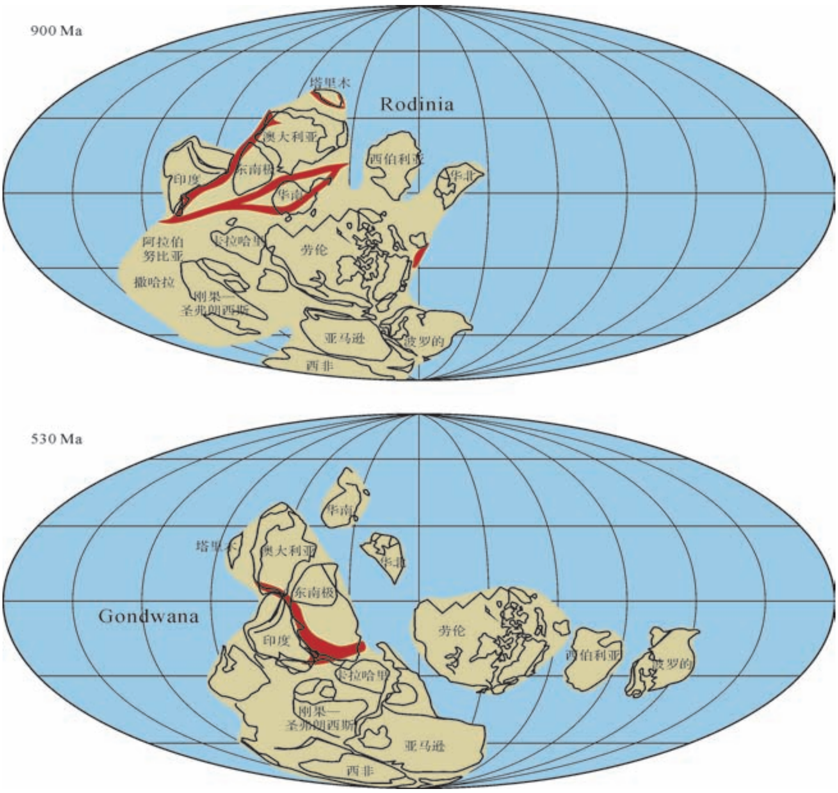

图 2　Rodinia 超大陆和 Gondwana 超大陆复原图[20]

Fig.2　Reconstruction of Rodinia and Gondwana[20]

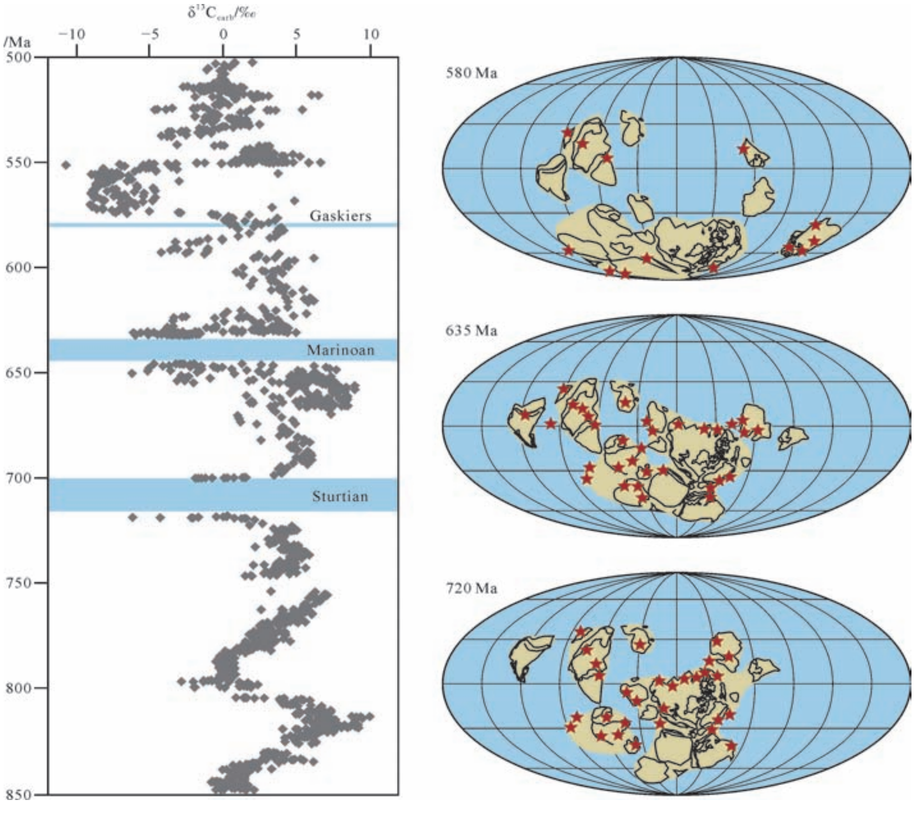

图 3　新元古代无机碳同位素记录[37-42]及冰期沉积物分布范围[43]

Fig. 3　Composite $\delta^{13}C_{carb}$ profile[37-42] and global distributions of Neoproterozoic glacial deposits[43]

进入全球性大冰期[54-55]。然而,鉴于一些冰期沉积物远距离搬运的特征,Hyde *et al.*[56]提出了“半融雪球”概念,认为当时地表并未完全被冰覆盖,赤道附近仍然能吸收足量太阳光能而防止冰盖的形成。考虑到地热等因素,Ashkenazy *et al.*[57]也指出冰期强烈的海水混合及赤道翻转环流会在大陆边缘形成无冰水域。这种无冰水域的存在保证了海洋与大气、陆地间的物质能量交换,为生物在冰期的繁衍和冰期后的快速复苏提供了保障。

成冰纪的冰川沉积物往往被一层碳酸盐岩所覆盖,其极负的 $\delta^{13}C_{carb}$ 值及与现代冷泉区相似的沉积构造指示了当时大规模的甲烷渗漏[58-59]。“雪球地球”期间,在永久冻土带和陆缘海区域可能形成巨量甲烷水合物;冰川消融初期水合物失稳分解产生的甲烷将进一步加快冰盖的融化,冰期积累的高浓度碳酸根离子与甲烷的氧化作用共同引发了盖帽碳酸盐岩的沉积[60]。BIF 型铁矿在新元古代的出现是这一时期极端气候条件的另一重要体现[61-62],其形成受控于海水中 H_2S 与 Fe^{2+} 的相对比例[63]。经 PAAS 标准化后轻稀土亏损、重稀土富集的配分模式,高 Y/Ho 比及弱的 Eu 正异常说明 BIF 来源于火山热液和海水的混合溶液[64-67]。冰期陆源输入硫酸盐含量的降低和洋中脊上覆静水压力的减小均会导致海底热液流体具更高的 Fe/S 比[68],缺氧停滞的海洋使 Fe^{2+} 得以累积并在间冰期氧化形成全球性的 BIF 铁矿[69-71]。这一结论与新元古代深海由硫化向铁化环境的转变相一致[72]。

1.3 氧化事件

海洋氧化还原条件的重建是古海洋研究的核心,对于解释水圈和大气圈、生物圈之间的相互作用至关重要。元古代海洋的水化学结构一直备受争论,其核心问题是硫化水体的形成机制与分布范围。“Canfield 海洋”模型认为中元古代—新元古代中期深部海水广泛发育硫化环境[73],并以此解释了真核生物在中元古代停滞演化的现象[74],1.8 Ga 首现的大型热水喷流沉积矿床似乎支持硫化海洋的假设[75]。然而,Li *et al.*[76]根据我国华南新元古代陡山沱组 Fe-S-C 化学系统的研究,提出了具有三维结构和动态变化的“硫化楔”模型(图 4)。随后,该模型被证明普遍适用于元古代到寒武纪早期的海洋环境[77-79]。对中元古代海洋的模拟计算也显示,其硫化面积可能不到总面积的 1%~10%[80]。事实上,由于陆源物质风化产生的硫酸盐是海洋中硫的主要来源,受早期海水硫酸盐储库和有机碳制造能力的限制,硫化水体主要发育在陆缘海区域,难以大范围扩张,也很难长期稳定维持。

最近,Zhang *et al.*[9]在我国华北下马岭组识别出了中元古代海洋“最小含氧带”(图 4)。“最小含氧带”海洋化学结构的存在表明当时大气氧含量已经足以维持水体下沉过程中氧气的消耗。虽然中元古代可能曾出现过弱氧化的底水环境,但深海的普遍氧化主要发生在新元古代晚期之后。阿曼、澳大利亚及华南等地报道的埃迪卡拉纪地层中强烈的 $\delta^{13}C_{carb}$ 负漂移被认为是深海氧化的重要证据[81-82]。加拿大纽芬兰地区 Conception 群的铁组分数据也说明 Gaskiers 冰期之后深部水体普遍充氧[83],这一时间与阿瓦隆底栖生物群的出现(579~565 Ma)大致对应[84-85]。

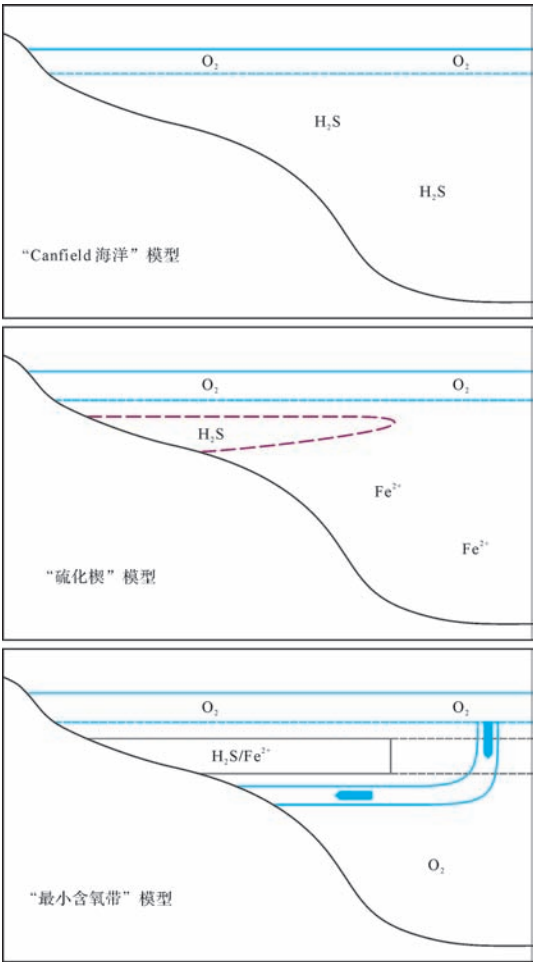

图 4 元古代海洋化学模型

“Canfield 海洋”模型[73];“硫化楔”模型[76-77];
“最小含氧带”模型[9]

Fig.4 Conceptual models for the redox structure of Proterozoic ocean

2　地质事件的地球化学记录

晚新元古代的另一显著特征即地层中碳、硫、锶等稳定同位素及钼、铀等氧化还原敏感元素的大幅波动（图 5），这些地球化学记录不仅反映了长时间尺度下的生物地球化学循环，还可能与许多全球性的地质事件密切相关。

2.1　碳同位素

碳是生命和埋藏有机质中最重要的组成元素。在有机质制造和降解过程中，均会产生一定量的碳同位素漂移，而有机质的制造和降解速率又往往与其地质背景有关。如冰期时，光合生物的有机质制造能力极低，伴随着 $\delta^{13}C_{carb}$ 的负漂；而冰期结束后，海洋中初级生产力的增长使大量富轻碳的有机质被埋藏，$\delta^{13}C_{carb}$ 出现正漂[92]。有机、无机碳同位素在地质历史中总体表现出一致的变化趋势，其中 $\delta^{13}C_{org}$ 在元古代早期的几次强烈负漂均被认为与微生物对甲烷的利用有关，暗示了当时大气中极低的氧含量[93-95]。

新元古代超大陆裂解、全球性冰期等事件的集中发生对碳同位素产生了明显影响。Gaskiers 冰期前，$\delta^{13}C_{carb}$ 以正值为主，仅在 Sturtian、Marinoan 两次冰期前后存在短暂负漂，冰期结束后迅速恢复至正值区间，平均值约为 +5‰[42,96]；而 Gaskiers 冰期之后，$\delta^{13}C_{carb}$ 发生了地质演化过程中最显著的一次负漂移

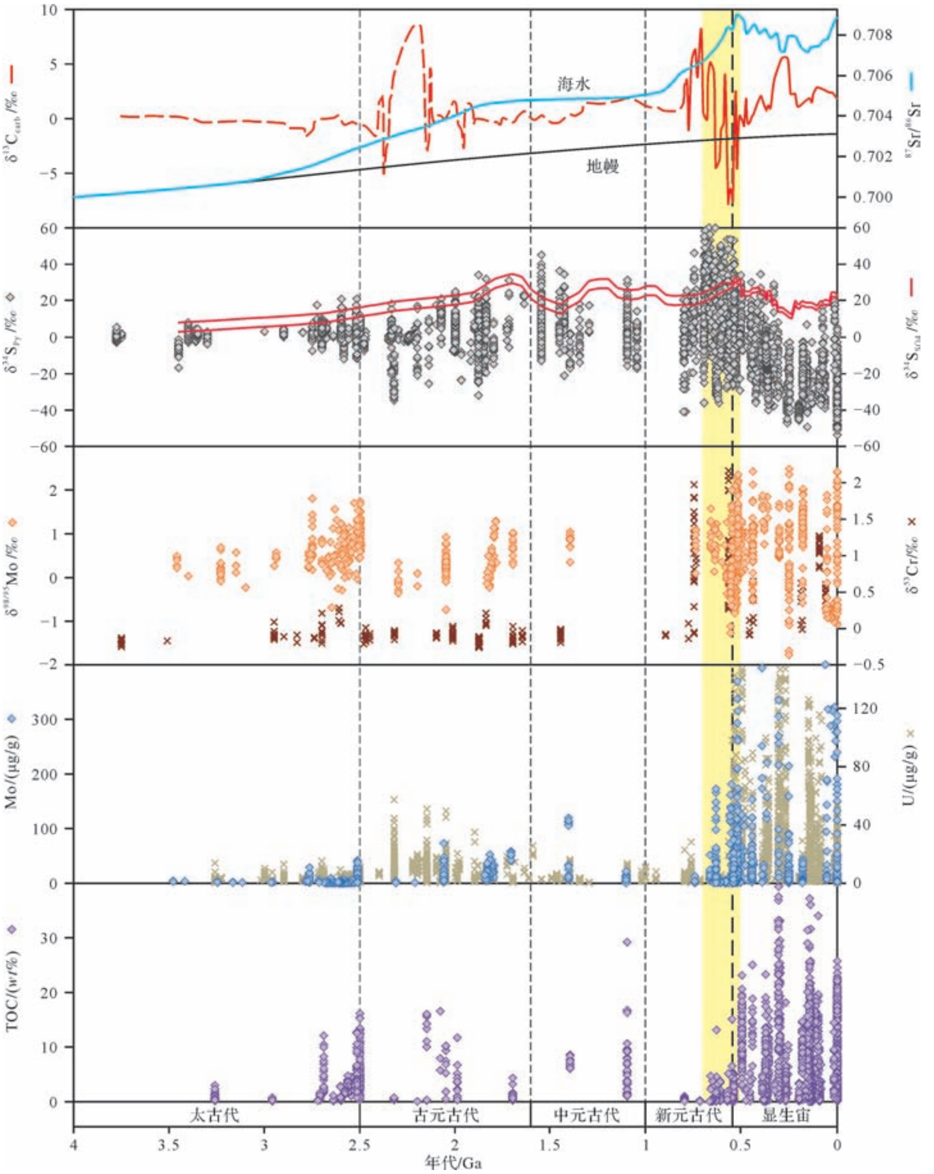

图 5　地质演化过程中的地球化学记录

无机碳、锶同位素[4]；黄铁矿、硫酸盐硫同位素[86]；钼[87-88]、铬同位素[89-90]；黑色页岩中的钼[91]、铀含量[88]；总有机碳[91]

Fig.5　Compilations of geochemical proxies through time

（图3）。尽管不能排除成岩改造的影响[97-99]，但大部分学者仍认为这种阶梯性特征与古海洋化学条件和有机质产率的改变有关[81,100-101]。新元古代氧化事件之前缺氧分层的海洋十分有利于生物有机质的制造和保存，$\delta^{13}C_{carb}$与$\delta^{13}C_{org}$的解耦说明其溶解有机碳库的规模可能10倍于同时期的无机碳库[102-104]。Gaskiers冰期后，大气氧含量的增加改变了海水的化学组成，深水有机碳被矿化从而参与到海洋表层的碳循环中，$\delta^{13}C_{carb}$由+5‰快速下降至−12‰，随后$\delta^{13}C_{org}$发生了相应负漂[82]。这种变化在全球许多地区的埃迪卡拉纪地层中均可进行对比，代表了这一时期深部水体的广泛氧化[39,81,105]。

2.2　硫同位素

海洋中的硫循环与碳循环十分相似，黄铁矿的埋藏同有机碳埋藏一样，有利于大气中氧气的累积，而硫酸盐和黄铁矿间的硫同位素分馏则可用于解译海水硫酸盐浓度的改变[106-108]。$\delta^{34}S_{Py}$和$\delta^{34}S_{SO4}$曲线在地质历史时期大致相互耦合，但$\delta^{34}S_{Py}$变化更为频繁，这主要是由于硫的氧化、还原和歧化反应容易受局部沉积环境的影响。太古代$\delta^{34}S_{Py}$平均值在0‰附近，说明当时还原性的海水中极度匮乏硫酸盐[109]。新元古代晚期硫同位素分馏明显增加，$\Delta^{34}S$由成冰纪末期的0‰左右增加至埃迪卡拉纪中期超过46‰（图5），这种显著的同位素分馏被归因于大气氧含量升高引起的硫的歧化代谢作用[73,81,110]。另外，硫同位素波动还可能与冰期或其他生物地球化学扰动有关[111-112]。例如，纳米比亚Rasthof组盖帽碳酸盐中$\delta^{34}S_{Py}$的异常高值（>60‰）就反映了冰期后海水中极低的硫酸盐浓度[112-113]。

2.3　锶同位素

新元古代初期$^{87}Sr/^{86}Sr$介于0.705 2~0.705 5[114]。Rodinia超大陆的聚合使得古老陆块被孤立于缺乏水分的内陆，而陆缘地区遭受风化剥蚀的主要是具$^{87}Sr/^{86}Sr$低值的新生地壳，类似的现象在Gonwana超大陆和Pangea超大陆聚合时同样存在[96]。晚新元古代到早寒武世期间，$^{87}Sr/^{86}Sr$由<0.706升高至>0.709[114-115]。Shields[115]对$^{87}Sr/^{86}Sr$的升高给出了3种可能的解释：1）$^{87}Sr/^{86}Sr$值更高的岩石遭受风化；2）伴随洋中脊扩张速率的降低，由洋中脊热液交代及玄武岩热液蚀变输入的Sr相对减少；3）地表风化作用增强。尽管不能排除假设1）发生的可能，但目前Sr、Nd同位素数据均未显示出放射性含量更高的岩石遭受了风化剥蚀[116]；而新元古代频繁的构造活动和海平面变化明显与假设2）相悖。因此，大陆风化作用在新元古代晚期至早寒武世的显著增强应该是$^{87}Sr/^{86}Sr$升高的主要原因，且这一推测与冰期后大气中极高的CO_2浓度相吻合[117]。

2.4　钼、铬同位素

钼同位素的分馏主要受氧化还原条件控制，氧化环境下海水中铁、锰（氢）氧化物微粒对钼的吸附作用会导致轻钼同位素富集，其分馏幅度可达3‰[118]；而在H_2S浓度大于11 μmol/L的还原条件下，MoO_4^{2-}定量转化为MoS_4^{2-}，几乎不发生同位素分馏[119-120]。因此，硫化沉积物与上覆水体具有相近的钼同位素组成。晚太古代2.6~2.5 Ga大气中氧含量出现过小幅增加，$\delta^{98/95}Mo$一度高达1.86‰[121]。随后，$\delta^{98/95}Mo$在新元古代中期之前一直维持在较低水平[122-124]。至新元古代晚期，$\delta^{98/95}Mo$开始显著升高（图5），并在520 Ma左右首次达到与现代海水相近的钼同位素值（+2.3‰），这说明当时海水中氧化沉积所占的比例已与现代海洋相当[88]。

富铁化学沉积岩（如BIF、富铁硅质岩）中铬同位素的变化也可用于示踪大气—海洋系统的氧化情况。新元古代之前的BIF与高温岩浆岩的$\delta^{53}Cr$没有明显差异，只在2.8~2.45 Ga和1.88 Ga存在两次小幅上升，而对沉积于Sturtian冰期的Rapitan组、Gaskiers冰期前后的Yerbal组和Cerro Espuelitas组的研究表明，其$\delta^{53}Cr$发生强烈正漂，最高达4.9‰[89]。另外，由于黑色页岩中富含大量自生铬，因此也可被用于铬同位素测试，加拿大Wynniatt组页岩（0.8~0.75 Ga）中高达2‰的$\delta^{53}Cr$正值可能揭示了新元古代氧化事件的序幕[90,125]。

2.5　氧化还原敏感元素

钼、铀等氧化还原敏感元素在沉积物中的富集程度除了与其自身的地球化学性质有关外，还受控于海洋中该元素储库的大小。由于在缺氧硫化环境下，海水中的钼、铀几乎被定量的扣留在沉积物中，因此硫化沉积物中的钼、铀含量能作为反映该元素在海水中可得性的指标[120,126]。太古代沉积物具有极低的钼、铀值，2 200~2 000 Ma前后钼、铀第一次明显富集，这次大气氧含量的增加同时对应了$\delta^{13}C_{carb}$正漂移所指示的有机碳大量埋藏[91,127-129]。中元古代硫化水体的发育对海水钼、铀储库影响显著，沉积物中钼、铀含量普遍较低。到新元古代中晚期之后，海洋的钼、铀储库再次扩大（图5），沉积物中钼的含量甚至在

Marinoan 冰期后不久就曾短暂地接近现代水平[130-131]。

3　地质事件与生物演化的耦合关系

在漫长的地球历史中，生命完成了从以原核细菌为主的荒芜状态向显生宙大型化、复杂化和躯体骨骼化的后生动物的转变。生物的生存和辐射并不是随意安排的，而是需要相当匹配的外周环境，包括温度、水质、氧气及物质能量等。真核藻类和后生动物在晚新元古代的集中演化与当时的地质背景可能存在极大联系。

3.1　超大陆事件与生物演化

超大陆裂解—重组对生物演化的影响主要体现在物质来源和生存环境方面。新元古代 Rodinia 超大陆的裂解导致全球性海侵，并形成了大范围的陆架盆地[132]。这些陆架盆地不仅具有丰富的陆源营养输入，并且可能存在区域性上升洋流的贡献[4,133]。为保证足够的光能进行光合作用，元古代海洋中大部分生物的演化仍是在表层水中进行的，但持续的有机质沉降会造成水体中营养物质缺失，若得不到有效补充，将极大程度上影响生物繁育的可持续性[134-135]。只有当营养物质通过上升洋流或陆源输入重新供应到表层时，生物的繁育才能持续存在。同时，海岸带水体的垂向混合为生物生存空间向海洋深部的扩展提供了可能。因此，超大陆裂解期常对应着富有机质黑色页岩的发育期，我国华南大塘坡组、陡山沱组等均沉积于 Rodinia 裂解时期，白垩纪时北大西洋开裂也使其两岸发育了多套优质烃源岩。

在为生物提供必要的生存环境和物质来源的前提下，超大陆事件还一定程度上影响着生物进化的方向。Peters *et al.*[136]提出世界范围内的寒武纪地层与其基底之间存在着一个稳定的大不整合面，说明当时强烈的风化作用可能将大量无机离子带入海洋中，使早寒武世海水的化学组成发生了巨大变化，以小壳动物群为代表的生物矿化机制在这一时期的产生可能就是对这种变化的应答[137-138]。

3.2　冰期事件与生物演化

冰期旋回的特征表现为温室—冰室环境的交替。温室条件下，海平面上升、浅海陆棚大面积形成。温暖湿润的气候使地表化学风化作用大大加强，随着陆源碎屑和淡水的注入，浅海将在较短的时间内变为富营养环境，十分利于浮游藻类的生长[139]。光合藻类产生的氧气可能使大气和浅海中的氧含量有所升高，为后生动物出现和演化提供基础[140]。我国大塘坡组底部锰矿和陡山沱组磷矿与黑色页岩的伴生关系即表明冰期后大量营养物质在海洋中的富集促进了生物的繁盛[141-143]。相比之下，冰室环境中生物的生存面临巨大的选择压力。一些生物的数量和种类在极冷事件中显著降低，而另外一些类群的遗传物质可能在此期间发生了明显变化。广泛分布的冰川使得海水变得停滞、连通性降低，之前温暖浅海中发育的微生物群落被隔离、封闭，由此产生了多样化的生存环境，这些都与冰期后真核生物的多样性演化关系密切[139,144]。此外，对成冰纪 BIF 的 P/Fe 比研究显示，当时海水的磷含量较元古代早期发生了极大幅度的增长[145]。冰川对大陆岩石的研磨作用会在冰退时将大量磷元素释放到海洋中[146]，从而为藻类的兴盛提供养料。

新元古代冰期见证了生物进化的重要革新。我国华南大塘坡组、陡山沱组二段和四段发育的黑色页岩分别记录了 3 次冰期后生物的勃发。Sturtian 冰期后，大塘坡组黑色页岩中甾烷分布的 C_{29} 优势和大量甲藻甾烷的发现，说明绿藻和沟鞭藻取代疑源类和菌藻类，成为沉积有机质的主体[147-148]；Marinoan 冰期后，褐藻等底栖藻类和动物胚胎化石开始出现，蓝田生物群和瓮安生物群是其中的典型实例[149-151]；Gaskiers 冰期后，以庙河生物群为代表的藻类多细胞化、大型化和多样性趋势明显[152]。三次冰期事件使得沉积有机质的母质来源由疑源类和菌藻类迅速演化为浮游藻类、底栖藻类和后生动物。由此可见，早期真核生物在冰期后较短的地质时限内就快速实现了多细胞化、组织分化、两性分化和形态多样化的转变。

3.3　氧化事件与生物演化

氧气含量的变化可能是与生物演化关系最为密切的限制性因素。作为真核生物专属生标的甾烷，其前体四环胆甾烷的形成需要分子氧的参与，而后生动物的呼吸和胶原蛋白的形成同样需要分子氧，因此氧气被认为是真核生物和后生动物出现必要的物质基础[153-155]。Payne *et al.*[156]对地质演化过程中生物类型的统计结果表明，古元古代和新元古代两次大氧化事件分别对应了原核生物向真核生物的演化及单细胞生物向多细胞生物的演化。多细胞藻类和动物化石记录在埃迪卡拉纪的突然增加不仅反映了后生动物数量和种类的变化，同时也说明了生命由无氧代谢向有氧代谢演化的一大进步。

对于氧化事件与生物演化之间的因果关系,有学者曾提出不同看法,认为新元古代末期浮游动物的牧食行为是导致深海氧化的主要原因[157-158]。然而,在埃迪卡拉纪地层中缺少以悬浮藻类为食的浮游动物的化石记录,但这一时期的深海至少已发生了幕式氧化[131,159]。事实上,已知最早的以藻类为食的浮游动物化石发现于加拿大西北部 Mount Cap 组(515~510 Ma)[160],滤食性海绵出现的时间虽然可能相对较早,但由于其主要依靠自由有机碳和细菌为食[161],因此对海洋表层的生态系统不会产生明显压力。

另外,作为呼吸耗氧生物,海绵等早期后生动物生存所需的最小含氧量大约为 0.5% PAL[162]。Planavsky *et al.*[90]根据铬同位素数据推测,中元古代极低的大气氧含量(<0.1% PAL)似乎是限制后生动物早期演化的关键因素。然而,Zhang *et al.*[9]对我国中元古代下马岭组沉积环境的模拟计算结果显示,当时的大气氧含量已高达4% PAL,这一发现可能需要研究者们重新评估氧气含量对生物演化的限制作用。

4 结语

新元古代的地球表层系统经历了一系列重大地质事件,这些地质事件与生物革新的同时发生,表明早期地球环境的变化与生物演化之间存在着密切的耦合关系。当环境条件突破某些关键性约束后,生物类群的丰度和分异度就可能出现爆发式的增长。值得一提的是,地质历史中类似的关键时段均伴随有大量黑色页岩及金属、非金属矿产的形成。因此,以某一时期各种地质事件为对象,开展古构造、古气候、古海洋、古生物等交叉学科的研究,不仅有利于我们了解地球系统的整体演化及各圈层间的相互作用,同时可以为多种沉积矿产及烃源岩发育机制的探讨提供独特价值。

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Geological Events and Their Biological Responses During the Neoproterozoic Era

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Abstract: The Neoproterozoic Era witnessed a series of geological and biological events which may have significantly changed the Earth's surface environment. These events are suspected to be linked and their temporal relationships have long been a focus of multidisciplinary studies. Superplume activity and true polar wander through the early Neoproterozoic led to the break-up of Rodinia supercontinent. Indeed, such a large perturbation of deep mantle dynamics exerted a crucial impact on the global cycles of O_2 and CO_2, thus further inducing the extraordinarily dramatic climate. Biological consequences of tectonic re-configuration are mainly reflected in nutrient availability and living conditions. The elevated upwelling and surface runoff could sustain persistent blooms of marine organisms. A Snowball Earth hypothesis has been proposed to explain the tropical glaciation. During times of widespread ice, there must be an intense environmental filter on the evolution of early life. Moreover, the subsequent rapid melting of glaciers may result in the explosion of productivity as well as the formation of major sedimentary minerals. Besides these geological and biological events, this period is also characterized by prominent fluctuations of geochemical proxies, which indicate great changes of atmosphere and ocean at this critical interval.

Key words: Neoproterozoic; supercontinent; glaciation; atmospheric oxygen level; biological events