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火星近现代地质过程与宜居环境演化

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摘　要：火星保存了自形成以来多期次地质作用的丰富记录，为研究行星宜居性的长期演化提供了独特窗口。然而，当前对火星近现代（亚马逊纪以来）地质过程与宜居环境演变的理解仍较为薄弱，这制约了我们对火星整体宜居性演化路径的完整认知，尤其是难以厘清其关键转变机制及现今环境状态的成因。近现代地质过程（如火山活动、撞击作用、水及冰川活动及风沙作用）不仅直接塑造了火星当前的地表环境，更记录了火星近期气候与地质变迁的历史，是揭示其宜居性演化晚期阶段特征与驱动机制的关键证据。本文系统总结了火星亚马逊纪以来主要地质过程的研究进展，在此基础上讨论了控制其宜居环境演化的关键因素，初步构建了火星宜居性评价指标体系，并对未来火星探测与研究的主要方向提出展望。亚马逊纪以来的地质过程对火星的宜居环境有着重要影响，未来探测需重点关注火星火山活动演化历史、撞击坑物质组成、水冰分布情况以及风蚀地貌成因演变。

关键词：地质过程；宜居环境；评价指标；火星探测；亚马逊纪

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Recent Geological Processes and Evolution of Habitable Environment on Mars

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Abstract：Mars preserves a rich record of multiple geological processes since its formation, providing a unique window into the long-term evolution of planetary habitability. However, the understanding of Martian recent geological processes (since the Amazonian) and habitable environmental evolution is still relatively weak, which constrains a comprehensive view of the overall trajectory of habitability on Mars and makes it difficult to clarify the mechanisms behind key transitions and the causes of its current environment state. Recent geological processes, such as volcanic activity, impact events, aqueous & glacial activity, and aeolian processes, not only directly shaped Mars' present-day surface environment, but also recorded the recent history of its climatic and geological changes. These processes thus constitute crucial evidence for revealing the characteristics and driving mechanisms of habitability evolution during the later stages of Mars. In this paper, we systematically summarize recent research progress on major geological processes since the Amazonian, discusses the key factors controlling the evolution of habitable environments, preliminary constructs an index

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system for habitability assessment on Mars, and proposes prospects for the main directions of future exploration and research. Geological processes since the Amazonian have had a significant impact on Mars' habitable environment. Future Mars exploration should prioritize focus on the evolutionary history of volcanic activity, the composition of impact crater materials, the distribution of water ice, and the origin and evolution of wind-eroded landforms.
Key words: geological processes; habitable environment; assessment index; Mars exploration; Amazonian

类地行星的宜居环境演化对于探索地外生命以及评估人类未来星际移民的可能性都至关重要(Cockell et al., 2016；Ehlmann et al., 2016)。火星是太阳系内与地球最为相似的行星。由于缺乏板块构造且风化与剥蚀率极低，其自形成以来的多期次地质作用能够较好地保存下来(Carr and Head, 2010)。火星的这一特征为研究行星宜居性的长期演化提供了独特窗口。因此，有关火星宜居性的研究一直是当前行星科学研究的热点与重点，也是火星科学与探测的首要科学问题(Michalski et al., 2013；赵宇鴳等，2020；Liu et al., 2022a；Xiao, 2023)。

早期美国开展的一系列火星探测任务，聚焦于寻找火星液态水和探索火星生命，发现了大量与液态水活动相关的证据，为火星宜居性演化研究奠定了坚实基础(Masursky, 1973；Carr and Clow, 1981；Kargel et al., 1995；Baker, 2001；Christensen, 2003；Ojha et al., 2015；Orosei et al., 2018)。我国首个火星探测任务“天问一号”于 2020 年 7 月成功发射，主要科学目标包括火星形貌与地质构造特征、土壤特征与水冰分布、表面物质组成等(Jia et al., 2018；耿言等，2018；Zou et al., 2021)。其中搭载的祝融号火星车在火星乌托邦平原发现了过去存在古海洋和现今仍有液态水活动的证据(Liu et al., 2022b；Lin et al., 2023；Qin et al., 2023；Wang et al., 2023；Xiao et al., 2023a；Li et al., 2025)，进一步丰富了我们对火星宜居性潜力的认识。“天问三号”任务将开展火星采样返回工作，其首要科学目标是探寻火星生命痕迹，其次是气候演变以及地质及内部过程(Hou et al., 2024, 2025)，有望在类地行星宜居性演化研究上取得重大突破。

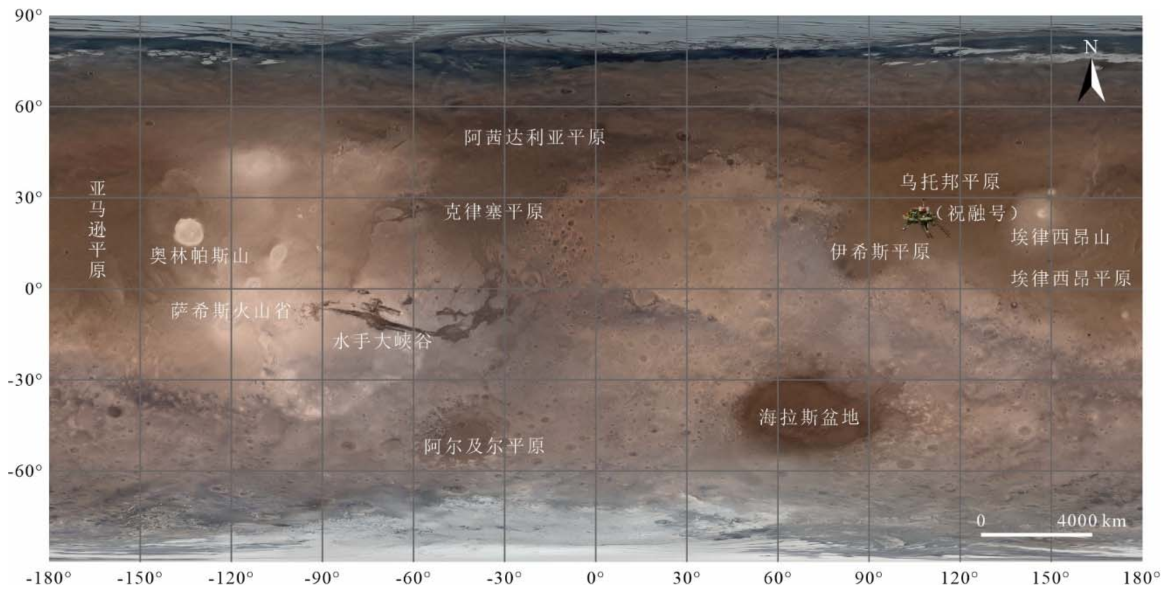

图 1　火星地貌分布。底图为天问一号中分辨率相机的全球彩色影像图(Liu et al., 2024a)，并覆盖在 MOLA 数字高程模型上

Fig.1　Distribution of Martian landforms. The base map is global color image of Mars from TW-1 Moderate Resolution Imaging Camera (Liu et al., 2024a), overlay on the MOLA DEM

火星的多种内外动力地质过程塑造了火星地貌的多样性（图 1），包括火山、撞击、水成、风成、冰川等地貌类型(Carr, 2007；肖龙，2013)，其形态特征和物质组成反映了火星的地质作用过程，也记录了火星气候环境变化的信息(Di Achille and Hynek, 2010；Xiao et al., 2012；Deng et al., 2020；王江等，2021；赵健楠等，2021；Grau Galofre et al., 2022)。相较于早期地质过程，火星亚马逊纪（约 30 亿年前至今）以来的近现代地质过程，具有直接地反映出当前火星地表-大气相互作用和地貌演化的独特优势(Diniega et al., 2021)。因此，对火星近现代地质过程和相关地貌的研究，可揭示火星地质改造的最新动态和当前气候环境演变，对探明火星宜居性，寻找潜在的地外生命和未来火星探测具有重要意义(Ehlmann et al., 2016；Sasselov et al., 2020；Bosak et al., 2021；肖龙，2022)。

本文总结了火星亚马逊纪以来的火山活动、撞击作用、水及冰川活动和风沙作用等近现代地质过程，分析了影响火星宜居演化的因素，提出了火星宜居性的评价指标体系，并对未来火星探测的方向做出了展望。

1　火星地质演化简史

在太阳原始星云出现后，星子不断吸积和碰撞增生并形成了太阳系的主要天体。火星的形成过程持续了几百万年(Kleine et al., 2004；Foley et al., 2005；Dauphas and Pourmand, 2011)，随后便开始了漫长的地质演化历史。火星的地质年代根据地质单元的相对层序以及撞击坑密度来确定，并被划分为四个时期(Tanaka, 1986; Hartmann and Neukum, 2001) （图 2）。从早到晚分别是：前诺亚纪（Pre-Noachian，约 4.6～4.1 Ga）、诺亚纪（Noachian，约 4.1～3.7 Ga）、西方纪（Hesperian，约 3.7~ 3.0 Ga）和亚马逊纪（Amazonian，约 3.0 Ga~现今）。其中，亚马逊纪是以火星表面广泛存在的、地质活动相对微弱的平原单元为主要特征的地质时期，并以亚马逊平原命名。

西方纪-亚马逊纪分界线的时限界定主要使用撞击坑大小—频率分布（CSFD）定年来测定。但不同的年代体系（如 Ivanov, 2001; Hartmann and Neukum, 2001; Hartmann, 2005 等）以及撞击坑密度界线（如 Tanaka, 1986; Werner and Tanaka 2011 等）会得到不同的绝对模式年龄。同时，由于火星撞击坑形成速率的不确定性，西方纪-亚马逊纪界线的年龄可能存在较大误差(Hartmann and Neukum, 2001; Carr and Head, 2010)。因此，西方纪-亚马逊纪的分界线目前还没有一个精确的年龄值，其大致范围在 2.9 ~ 3.3 Ga (Hartmann and Neukum, 2001; Werner and Tanaka 2011; Tanaka et al., 2014)。本文所使用的西方纪-亚马逊纪界线年龄“～3.0 Ga”是一个认可度较高的参考值（例如：Carr and Head, 2010; Grady, 2020; Wordsworth et al., 2021; Du et al., 2023 等）。

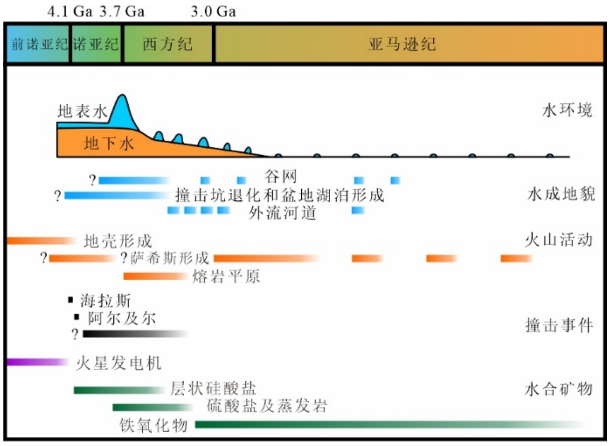

图 2　火星表面主要事件时间轴（修改自 Ehlmann et al., 2011；Wordsworth et al., 2021；Du et al., 2023；Kite and Conway, 2024）

Fig.2　Timeline of major events on the Martian surface (modified from Ehlmann et al., 2011；Wordsworth et al., 2021；Du et al., 2023；Kite and Conway, 2024)

由于诺亚纪强烈的地质作用改造，前诺亚纪的地质记录保留较少(Carr and Head, 2010)。尽管如此，地貌证据和数值模拟表明，火星在前诺亚纪发生过多起大型撞击事件，且南北二分性也很可能在此阶段形成(Nimmo and Tanaka, 2005；Nimmo et al., 2008；Carr and Head, 2010)。同时，磁异常分布表明，前诺亚纪的火星具有全球性磁场(Acuña et al., 1999；Mittelholz et al., 2020)。而来自火星陨石的同位素证据则支持该时期发生过强烈的火山活动(Hu et al., 2019)。

诺亚纪以海拉斯盆地的形成为底界(Carr and Head, 2010)，期间地质过程强烈，撞击事件、火山活动以及水岩相互作用等频繁发生。晚期重轰炸（约 4.1 ~ 3.8 Ga，Lowe and Byerly, 2018）使火星表面形成了多个大型的盆地。强烈的火山活动造就了萨希斯火山省的大部分区域，同时水流谷网在此期间大面积分布(Fassett and Head, 2008)。在晚诺亚纪，撞击、风化和侵蚀强度急剧下降，同时也形成了诸多古湖泊和三角洲。

西方纪时期火山活动仍旧持续，并使得约 30 %的火星地表发生重塑(Head et al., 2002)。西方纪存在着偶发性的大洪水(Carr and Head, 2010)，水成地貌（如外流河道、冲积扇等）在该时期大量形成(Grant and Wilson, 2011；Goudge et al., 2017)。火星的构造变形在晚诺亚纪及早西方纪出现峰值(Andrews-Hanna and Broquet, 2023)，随后应变速率急剧下降。

亚马逊纪占据了火星历史的大半，期间存在火山和水活动(Neukum et al., 2010；Zhang et al., 2023)，且火山活动的频率和强度都比较弱，撞击事件则一直持续到了现今，而亚马逊纪以来的冰川和风沙作用在火星表面尤为显著(Carr and Head, 2010；刘洋等，2021a)，对早期地质体的改造明显。

2　火星亚马逊纪以来的地质作用

地质过程及其形成的相关地貌和产物是我们认知火星的现状、了解火星过去的窗口 。亚马逊纪以来的地质过程，包括火山活动、撞击作用、水及冰川活动以及风沙作用。

2.1　火山活动

火星的火山活动存在于各个时期，并发育了大量的火山地貌(Carr, 1973；Xiao et al., 2023b；Michalski et al., 2024)。萨希斯（Tharsis）和埃律西昂（Elysium）地区的火山活动都持续到了晚亚马逊纪(Werner, 2009；Robbins et al., 2011；Xiao et al., 2012)。

作为火星最大、保存最完好的火山构造单元(Hauber et al., 2009)，萨希斯火山省持续活跃了超过 37 亿年(Werner, 2009; Zhong, 2009; Krishnan and Kumar, 2023)。长期的火山活动使得萨希斯生成了奥林帕斯（Olympus）、阿尔巴（Alba）等大型盾状火山以及 1100 余个小型火山口(Richardson et al., 2021；Pieterek et al., 2022)。晚亚马逊纪的火山活动在萨希斯火山省普遍存在，尤其以各大盾状火山附近最为明显(Bleacher et al., 2007；Hauber et al., 2011；Pieterek et al., 2022；Krishnan and Kumar, 2025)（图 3a）。熔岩流年龄显示(Hauber et al., 2011；Krishnan and Kumar, 2023)，萨希斯北部的熔岩流活动持续至 500 Ma 以内，且存在年龄约 10 Ma 的年轻喷发产物。火山口、地堑和熔岩流的年龄和空间分布表明，阿尔巴火山下方可能存在由地幔柱驱动的长期活跃的岩浆房和地壳下的岩浆底侵(Krishnan and Kumar, 2023)，其在晚亚马逊纪向南迁移，并形成现今观测到的火山-构造复合地貌。

埃律西昂火山的复苏活动始于晚亚马逊纪（<350 Ma）(Broquet and Andrews-Hanna, 2023)，形成了巨大的裂隙式喷发的熔岩流、低矮的火山盾以及堑沟群(Voigt and Hamilton, 2018)。同时地质观测还表明，埃律西昂火山东南侧的刻耳柏洛斯堑沟群（Cerberus Fossae）存在一个年龄约 53～210 ka 的火山碎屑沉积物（图 3d）(Horvath et al., 2021；Moitra et al., 2021)，代表了火星上最年轻的一次火山喷发。地球物理证据也支持了刻耳柏洛斯沟的年轻火山活动(Stähler et al., 2022；Broquet and Andrews-Hanna, 2023)，并认为埃律西昂的火山活动可能是由一个直径约 3600 ~ 4000 km 的活跃地幔柱驱动的，该推断是模型反演得到的最佳范围，并非直接观测结果。此外，埃律西昂平原的熔岩流体积估算显示(Voigt et al., 2023)，在晚亚马逊纪仍存在大规模的岩浆喷发事件。

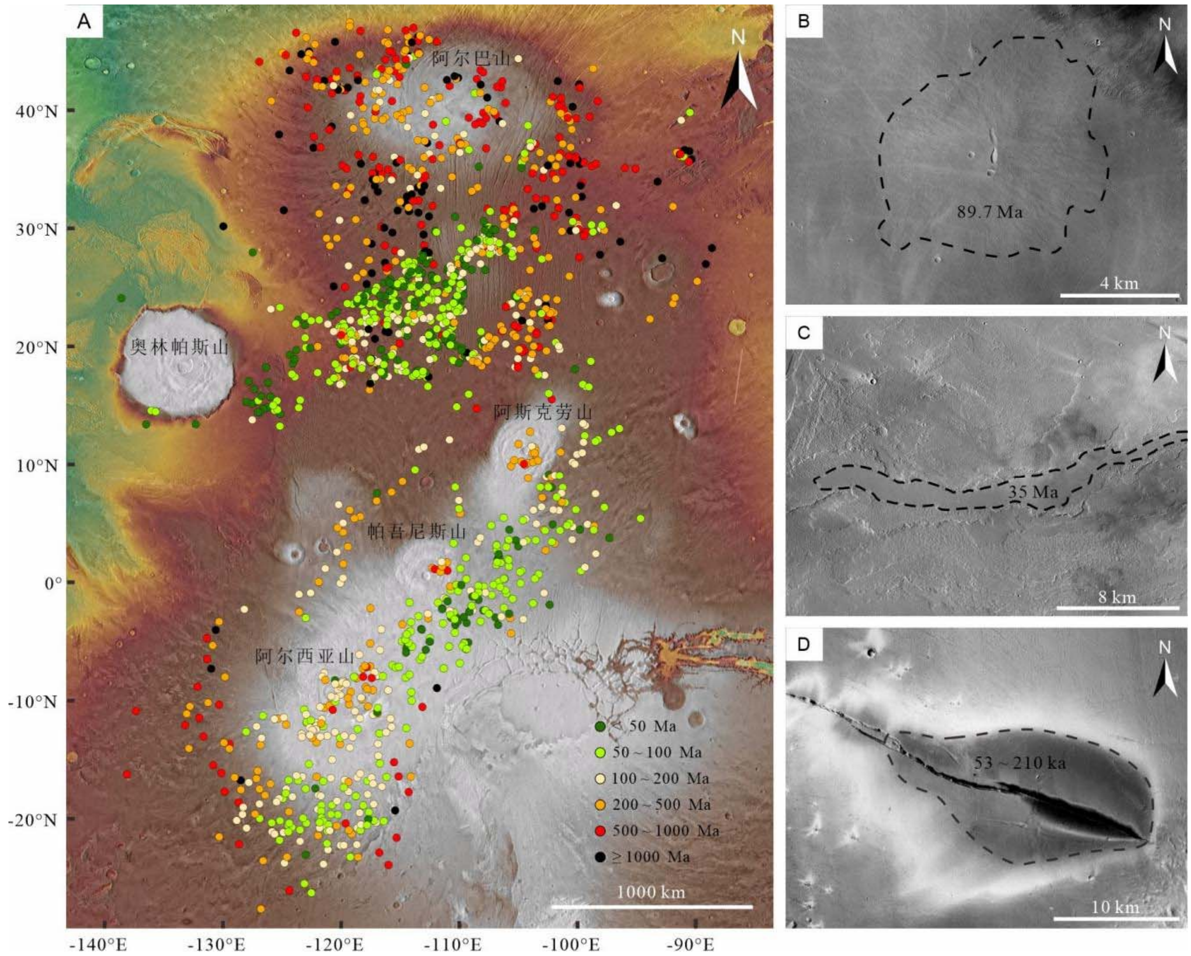

图 3 （A）萨希斯火山省内熔岩流的空间和年龄分布。图中不同的颜色点代表了不同的年龄范围，展示了亚马逊纪以来长期的火山活动。熔岩流年龄数据来自 Pieterek et al., 2022；Krishnan and Kumar, 2023, 2025；（B）和（C）萨希斯火山省内两处年轻的火山活动特征，其中 B 为阿尔西亚（Arsia）山一小型盾状火山（黑色虚线）以及相应的熔岩流，年龄为 89.7 Ma，C 为奥林帕斯山附近的一处熔岩管供给型熔岩流（tube-fed lava flow）（黑色虚线），年龄为 35 Ma。中心坐标 B：-120.83° E，-9.66° N，C：-117.88° E，24.68° N；（D）位于埃律西昂刻耳柏洛斯堑沟群的年轻火山单元，年龄为 53 ~ 210 ka，黑色虚线显示了其大致范围，中心坐标 165.75° E，7.93° N。其中，图 A 为 THEMIS 日间影像叠加在 MOLA 数字高程模型上，图 B-D 均为 CTX 影像镶嵌图

Fig.3 (A) Spatial and age distribution of lava flows within the Tharsis volcanic province. Different color dots represent different age ranges, demonstrating long-term volcanic activity since the Amazonian. The age data of lava flows from Pieterek et al., 2022；Krishnan and Kumar, 2023, 2025. (B) and (C) illustrate two young volcanic activity features within the Tharsis volcanic province, where B shows a small shield volcano (black dashed line) and corresponding lava flow emanating from the small shield volcano along the caldera of Arsia Mons, with an age of 89.7 Ma, and C shows a tube-fed lava flow (black dashed line) near the Olympus Mons, with an age of 35 Ma. Central coordinates of B: -120.83°E, -9.66°N, C: -117.88°E, 24.68°N. (D) Young volcanic unit located in the Cerberus Fossae of Elysium, with an age of 53~210 ka, and the black dashed line shows its approximate range, central coordinates 38.83°E, 45.59°N. Among them, Fig. A is THEMIS Day image overlaid on the MOLA DEM, Fig. B-D are all CTX Mosaic

2.2 撞击作用

火星表面分布有密集的撞击坑，代表了频繁的撞击事件。根据撞击规模可以将撞击坑分为简单撞击坑、复杂撞击坑和多环撞击盆地。火星表面不同区域的撞击坑密度存在显著差异，这表明火星表面的年龄范围跨度很大(Ehlmann et al., 2016)。模拟撞击频率表明，火星在过去的 40 亿年中受到超过 13 万个撞击体的影

响(Hartmann and Neukum, 2001)，形成了超过 38 万个直径大于 1 km 撞击坑(Robbins and Hynek, 2012)。亚马逊纪以来的撞击频率急剧衰减，但也仍然有约 5000 个复杂撞击坑（直径大于 6 km）在此期间形成(Morbidelli et al., 2018；Cox et al., 2022)。

火星上有一类具有溅射毯特征的特殊撞击坑，它们周围包裹有一圈呈放射状的层状溅射物。此类撞击坑也被称为壁垒撞击坑（Rampart crater）（图 4a），大多形成于亚马逊纪(苟盛等，2021)。溅射毯表现出了明显的流动性，被认为是火星表面水、冰大量参与的结果(Wohletz and Sheridan, 1983)，因此，壁垒撞击坑往往和地下水冰层联系在一起(Reiss et al., 2005；Ma et al., 2023)。此外，位于火星北半球的李奥（Lyot）撞击坑（图 4b），因其具规模巨大（直径约 225 km）、年龄相对年轻、位于北部低地等特点，成为了广泛关注的研究对象。人们认为该撞击过程穿透了火星地表下的水圈/冰冻圈(Russell and Head Iii, 2002；Weiss et al., 2017)，并将地下水释放到撞击坑内部，是探测深层地下水的独特地点。

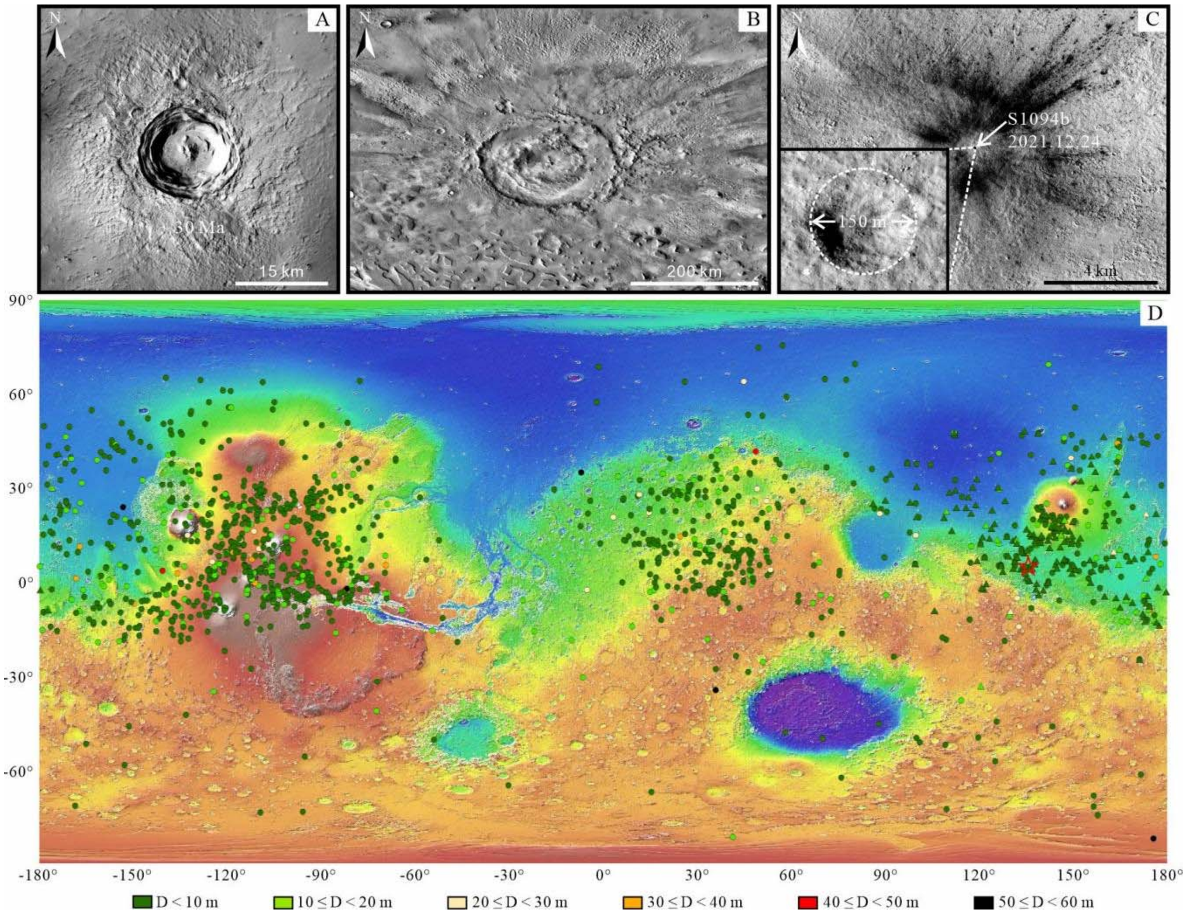

图 4　（A）位于伊希斯平原（Isidis Planitia）的壁垒撞击坑，年龄约 30 Ma (苟盛等，2021)，中心坐标 83.75° E，12.66° N；（B）形成于早亚马逊纪的李奥撞击坑，中心坐标 29.35° E，50.51° N；（C）由洞察号观测到的发生在 2021 年 12 月 24 日的撞击事件（编号 S1094b），此次撞击形成了一个直径约 150 m 的撞击坑，中心坐标-170.17° E，35.11° N。（D）1977 ~ 2022 年间火星上生成的新撞击坑分布图（部分），数据来自 Daubar et al., 2022（用圆形表示）；Bickel et al., 2025（用三角形表示），红色星号为洞察者号着陆点，不同的颜色点代表着不同的撞击坑直径范围。其中，图 A 为 CTX 影像镶嵌图，图 B 为 THEMIS 日间红外影像，图 C 为 CTX 图像（图像 ID：U05_073077_2154_XI_35N170W），左下角的小框为为 HiRISE 图像（图像 ID：ESP_073077_2155），图 D 为 MOLA 全球彩色阴影浮雕图

Fig.4　(A) Rampart crater located on Isidis Planitia, approximately 30 Ma old (Gou et al., 2021), central coordinates 83.75°E, 12.66°N. (B) Lyot crater, formed in the Early Amazonian, central coordinates 29.35°E, 50.51°N. (C) The impact event (S1094b) observed by the InSight on December 24, 2021, which formed a crater approximately 150 m in diameter, central coordinates -170.17°E, 35.11°N. (D) Distribution of new impact craters formed on Mars from 1977 ~ 2022 (partial). Data from Daubar et al., 2022 (represented by circles)；Bickel et al., 2025 (represented by triangles). The red asterisk represents the landing site of the Insight mission, and different color dots represent different diameter ranges. Figure A is the CTX Mosaic, Figure B is the THEMIS DayIR Mosaic, Figure C is the CTX image (image ID: U05_073077_2154_XI_35N170W), the small box in the lower left corner is the HiRISE image (image ID: ESP_073077_2155), and Figure D is the MOLA Global Color Shaded Relief

火星上的撞击事件持续到了现今。1977 年至 2021 年间，火星表面形成了超过 1200 个撞击坑（Daubar et al., 2022，图 4d）；自 2018 年 12 月以来，借助洞察号已观测到 179 起撞击发生在其着陆点附近（Bickel et al., 2025，图 4d），其中，有接近一半以撞击坑群的形式出现。此类撞击事件的规模普遍较小，撞击坑直径绝大多数在 100 m 以下。例如，在洞察号任务期间，观测到一个很可能是由明显减速的撞击体造成的直径约为 1.5 m 的撞击坑(Daubar et al., 2020)，极小规模的撞击观测加深了人们对小型撞击地震可探测性的理解。此外，火星勘测轨道飞行器（MRO）观测到于 2021 年下半年形成的两个直径>130 m 的撞击坑（S1094b 与 S1000a，图 4c，Posiolova et al., 2022），是迄今为止在火星表面观察到的最大的两次撞击坑形成过程，其形成的地震波传播特征为研究火星的地壳结构提供了独特机会(Kim et al., 2022)。

2.3　水及冰川活动

亚马逊纪以来，火星经历了大量的水损失，当前的火星是一个寒冷干旱的沙漠星球，其表面无法存在稳定液态水，大部分水储存在两极和地下，大气含水量极低(Martínez and Renno, 2013；Brown et al., 2016；刘洋等，2021b；赵健楠等，2024a；Xu et al., 2025)。在中高纬度地区，水主要以孔隙冰或过剩冰的形式保存在风化层中(刘正豪等，2024)。而现今的地下水多通过地壳水合作用储存在矿物中(Scheller et al., 2021；Du et al., 2023)，不过也不能排除存在深层地下水体的可能性(Kurokawa et al., 2014；Orosei et al., 2018；Abotalib and Heggy, 2019)。近期，基于洞察号探测器收集的地震波数据，有研究提出火星地下可能存在巨大水体的假设(Wright et al., 2024)。该假设为进一步探索火星的水资源指引了新方向，但仍需更多的观测和研究来验证。

祝融号在乌托邦平原的探测为研究火星近现代水活动提供了重要参考。着陆区探地雷达结果表明，地下的层状结构(Li et al., 2022)指示着晚西方纪到亚马逊纪出现了间歇性的洪水沉积，同时地下 80 米内不存在液态水，但无法排除存在盐冰的可能性。而识别出的地下多边形则与冻融循环有关(Zhang et al., 2024)，很可能是在高倾角时期形成，并认为在晚西方-早亚马逊纪火星的水活动发生了显著变化。光谱和地形相机识别出的含水矿物以及沙丘结壳说明(Liu et al., 2022b；Qin et al., 2023；Zhao et al., 2023a)，亚马逊纪的火星水活动比以往认为的要更活跃，祝融号着陆点（北部低地）可能存在着现代水。着陆区横向风成脊表面的多边形特征也被认为是水活动和大气-地表水交换的产物(Wang et al., 2023)。

火星亚马逊纪以来，冰川的活动更为显著，形成了一系列冰沉积物、黏性流动特征（图 5A～D）和浅地表水冰升华地貌(刘正豪等，2024)。冰川活动的一个重要驱动力是火星自转轴倾角的周期性变化，其导致太阳辐射在火星表面的分布发生改变，从而影响水冰的稳定性和分布(Head et al., 2003)。在过去的 20 Ma 里，火星的倾角在 15～45°之间变化，而在 100 Ma～1 Ga 之间，其倾角可能会超过 60°(Laskar et al., 2004)。在高倾角时期，极地和高纬地区的水冰会向中低纬度迁移(Forget et al., 2006；Byrne, 2009)。而在低倾角时期，水冰则会在极地及高纬地区重新积累。自转轴倾角的周期性变化使水冰得以在火星表面不断重新分布，并造成冻融循环，形成河谷（图 5E）、多边形等地貌(Dickson et al., 2009；Fassett et al., 2010；Zhang et al., 2024)。冰川的活动通过该种方式储存和释放水，从而在调节火星的气候方面有着重要作用。

此外，撞击作用也会触发水活动。以北部平原的李奥撞击坑为例，该坑北部溅射毯外缘发育了大量的河谷网络，其形态以辫状河道为主(Harrison et al., 2010；Weiss et al., 2017)（图 5F）。此大型亚马逊纪河流系统的形成可归因于撞击作用，撞击或融化地表冰并释放地下水，或促使喷出物脱水从而形成河谷网络。

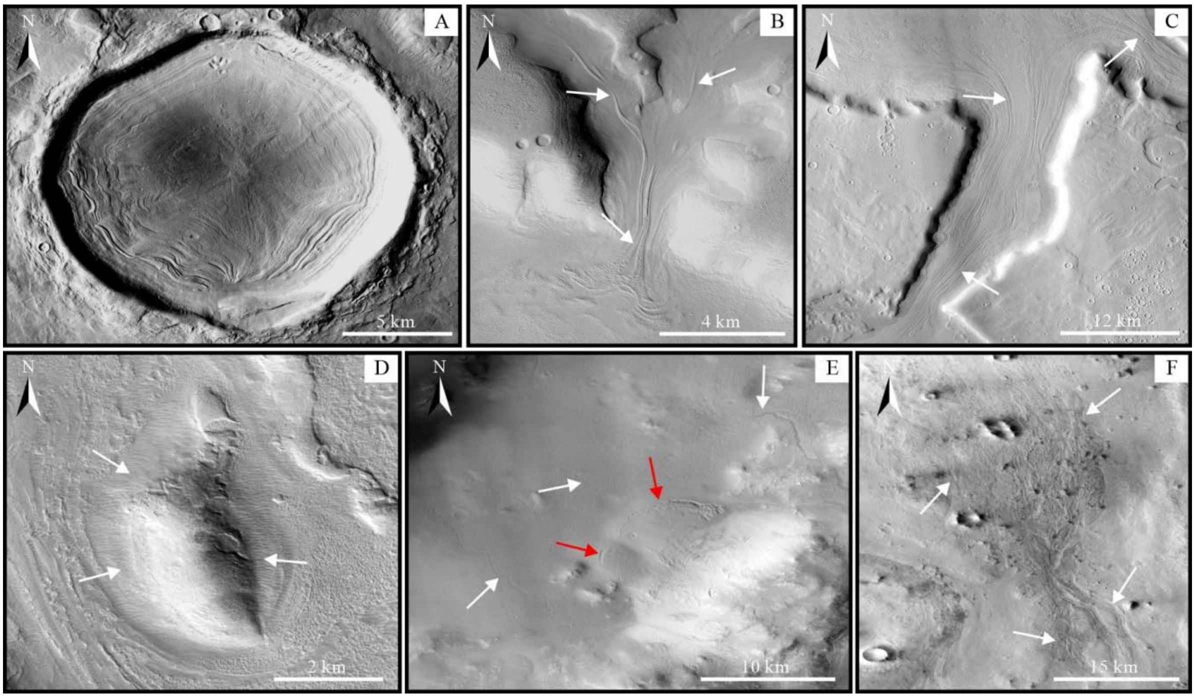

图 5　火星亚马逊纪水及冰川地貌。（A）冰川黏性流动特征中的同心圆撞击坑填充，中心坐标 87.91° E，36.11° N；（B）和（C）冰川黏性流动特征中的谷底线状充填沉积物（白色箭头），中心坐标 B：29.56° E，41.28° N，C：35.06° E，39.65° N；（D）冰川黏性流动特征中的叶状岩屑坡（白色箭头），中心坐标 38.83° E，45.59° N；（E）由冰川融化形成的河谷（白色箭头），红色箭头指向冰川地貌叶状岩屑坡，中心坐标 30.92° E，49.19° N；（F）受撞击作用影响而形成的亚马逊纪河谷网络（白色箭头），以辨状河道为主，中心坐标 26.51° E，57.23° N。图中所有影像均为 CTX 影像镶嵌图

Fig.5　Water and glacial landforms on Amazonian Mars. (A) Concentric crater fill (CFF) in the viscous flow features (VFFs) of glaciers, central coordinates 87.91°E, 36.11°N. (B) and (C) Lineated valley fill (LVF, white arrows) in the VFFs, central coordinates of B: 29.56°E, 41.28°N, C: 35.06°E, 39.65°N. (D) Lobate debris aprons (LDA, white arrows) in the VFFs, central coordinates 38.83°E, 45.59°N. (E) The fluvial valley formed by ice melting (white arrow), and the red arrow indicates LDA of the glacier landform, central coordinates 30.92°E, 49.19°N. (F) The Amazonian fluvial networks (white arrow) formed by impact effect being dominated by braided channels, central coordinates 26.51°E, 57.23°N. All the images are CTX Mosaic

2.4　风沙作用

火星是太阳系内除地球之外唯一形成风成地层（Aeolian strata）的天体，其稀薄的大气与复杂的大气环流系统塑造了独特的风沙环境(Grotzinger et al., 2005；Banham et al., 2018；赵健楠等，2024b)。观测显示，火星表面和昼夜温差可达 100℃以上，巨大的温差引发的大气热对流效应剧烈，使火星的风速最高可达 50 ~ 100 m/s，且风向多变(Badescu, 2009；Savijärvi et al., 2020；Piqueux et al., 2024；赵健楠等，2024b)。在这种大气动力条件下，火星的尘暴活动有着显著的季节性：在太阳经度 0° ~ 180°表现为非沙尘季节，而 180° ~ 360°期间大气沙尘含量增加，并可能发展为全球性尘暴(周旭等，2024)。

相比其他地质过程，风沙作用对火星表面的改造能力相对较弱，其主要体现在对火星表面松散沉积物的搬运和再沉积。在火星的低重力、低大气压条件下，风沙作用在火星表面十分普遍，其在火星亚马逊纪

以来扮演着重要角色，为研究地表-大气相互作用提供了重要支撑(Diniega et al., 2021；Liu et al., 2023)。

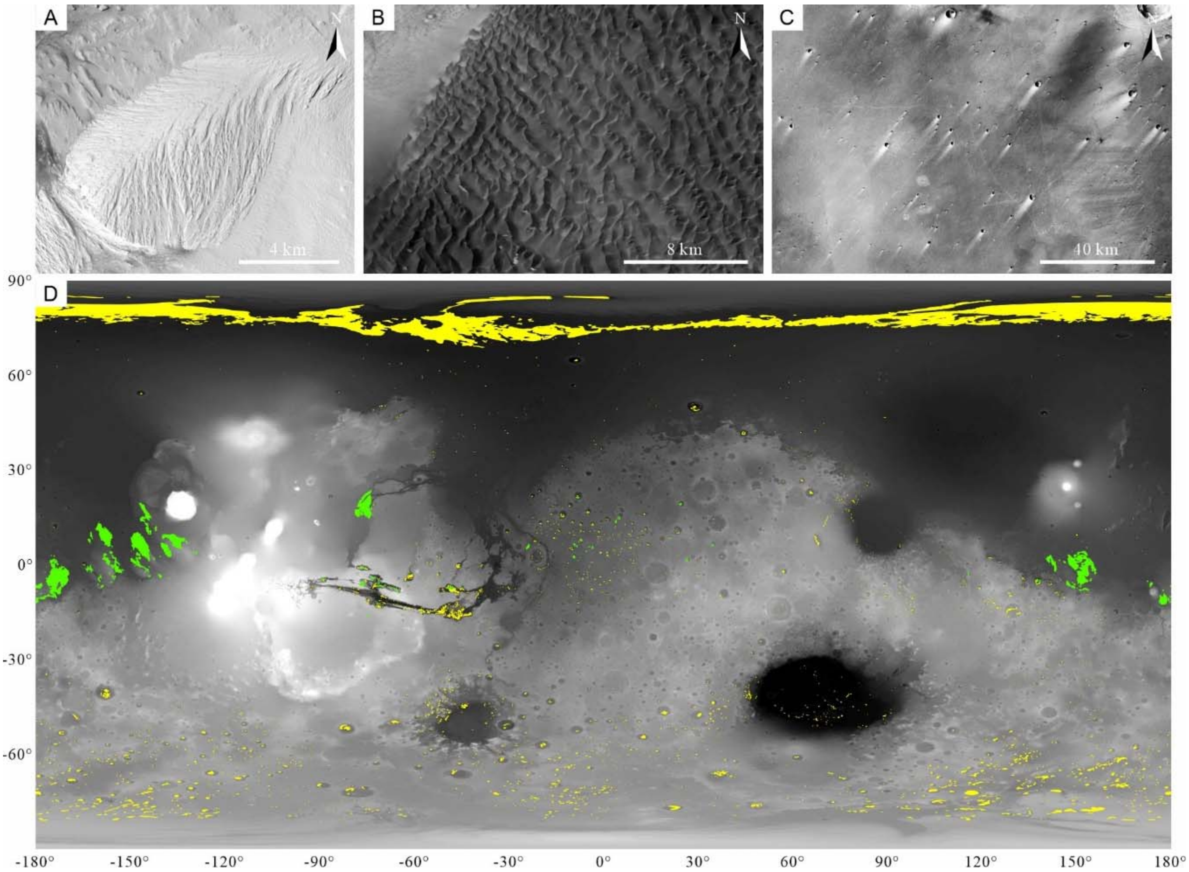

图 6 （A）位于盖尔撞击坑的雅丹地貌，中心坐标 137.52°E，-4.80°N；（B）位于南半球中纬度的沙丘，中心坐标 30.13°E，-47.60°N；（C）在克律塞平原上广泛分布的风纹，中心坐标-41.35°E，26.02°N；（D）火星全球沙丘和雅丹地貌分布图，图中黄色多边形代表沙丘，绿色多边形代表雅丹。沙丘数据来自 Hayward et al., 2014；Fenton, 2020，雅丹数据来自 Liu et al., 2020。其中，图 A-C 均为 CTX 影像镶嵌图，图 D 为 MOLA-HRSE 混合数字高程模型

Fig.6 (A) Yardang landform in the Gale Crater, central coordinates 137.52°E, -4.80°N; (B) Dunes in the mid-latitudes of the Southern Hemisphere, central coordinates 30.13°E, -47.60°N; (C) Widespread distributed of wind streaks on the Chryse Planitia, central coordinates -41.35°E, 26.02°N; (D) Global distribution map of dunes and yardangs on Mars, with yellow polygons representing dunes and green polygons representing yardangs. Dunes data from Hayward et al., 2014；Fenton, 2020, and yardangs data from Liu et al., 2020. Figures A-C are CTX Mosaic, and Figure D is MOLA-HRSE blended DEM

风沙作用在火星表面形成了雅丹、沙丘、风成条纹、风棱石、风蚀坑、横向风成脊等诸多风成地貌（图 6）(李继彦和董治宝，2016；王江等，2021)。其中，沙丘和沙波纹在火星上广泛分布，其在北极层状沉积物的周围形成了环绕北极的广阔沙漠海，其他地区则主要分布在撞击坑、河谷等地形凹陷处(Tsoar et al., 1979；Bridges et al., 2012；Li and Dong, 2022)。沙丘和沙波纹在现今火星环境下依然活跃，例如，赫舍尔撞击坑（Herschel Crater）内的沙丘移动速度约为 0.2 m/yr，沙波纹移动速度约为 0.3 m/yr(Cardinale et al., 2016)；而子午线高原的因代沃（Endeavour）撞击坑沙丘平均移动速度高达 9 m/yr(Chojnacki et al., 2011)。此外，沙丘的移动速度和其高度呈现出负相关特征(Diniega et al., 2021)。最高沙通量区域集中在大浅滩（Syrtis Major）、赫勒斯滂山脉（Hellespontus Montes）和北极沙漠区（The North Polar Erg）(Chojnacki et al., 2019)。

亚马逊纪以来，风蚀过程在火星表面物质分布和地貌形态重塑中发挥了重要作用。火星表面不同区域

的风沙侵蚀速率有所差异，埃律西昂平原的平均表面侵蚀速率为 $10^{-2} \sim 10^{-3}$ m/Myr(Sweeney et al., 2018)，而在较古老的子午线平原，侵蚀速率为 1～10 m/Myr(Golombek et al., 2014)。火星上的风蚀地貌主要有雅丹和风棱石，雅丹地貌主要集中分布在低纬度地区，而风棱石在火星上广泛分布(李继彦和董治宝，2016；Liu et al., 2020；王江等，2021)。此外，两极高纬度区域（南北纬 60° 以上）广泛分布有巨大的条形切沟，它们也可能是风蚀形成的。例如，南极层状沉积物中分布的峡谷（Chasmae），是持续的下行风侵蚀的结果(Howard, 2000；Koutnik et al., 2005；Smith et al., 2015)。

3　火星近现代宜居环境演化

3.1　影响宜居性的因素

火山活动、撞击事件、冰川活动、水岩相互作用（化学风化和蛇纹石化）、大气活动等诸多因素，在火星近现代宜居环境演化过程中具有重要影响。

3.1.1　火山活动　火山活动与生命的起源及演化有着密切关联。对地球生命而言，火山地形可能是陆地生命最早的栖息地(Djokic et al., 2017)，其喷发过程为理解极端环境下微生物群落的发展提供了特殊视角。在火星上，强烈的火山喷发可能会提供大量水和其他挥发性物质(Ramirez et al., 2014；Pan et al., 2017)，形成温室环境；同时，火山与水圈或冰圈的相互作用可引发局部热液活动，提供地热、液态水和化学能(Schulze-Makuch et al., 2007)。

火星亚马逊纪的火山活动强度总体较弱，但其对近现代宜居环境的塑造仍不可忽视。当火山活动与地表或近地表冰相结合时，形成的宜居环境在亚马逊纪将会得到延续(Scanlon et al., 2015；Moreras-Marti et al., 2021)。埃律西昂地区发现的年轻岩浆活动迹象(Horvath et al., 2021)进一步表明，现今火星地下可能仍存在热液环境。同时，模型分析表明(Sholes et al., 2017)，在亚马逊纪，火山脱气所释放的硫化物和二氧化碳等挥发物也可能促使火星局部形成还原性环境，这对生命过程具有潜在意义。此外，亚马逊纪火山活动形成的熔岩管(Bleacher et al., 2007)等特殊地形兼具温度稳定性与辐射防护能力，是保存生命痕迹的理想场所(Hadland et al., 2024；佘星阳等，2024)。

在亚马逊纪，火山活动还通过多种方式参与火星的物质循环。一方面，火山活动将未成熟水以火山熔岩和岩浆的形式释放到大气层(Jakosky, 2021)，参与随后的季节性循环，而由于亚马逊纪火星的磁场缺失以及稀薄大气，其最终将流失至太空（图 7）；另一方面，近期或正在进行的岩浆活动也可能是火星大气中瞬时甲烷的来源，其可能源于火山脱气的直接排放，也可能通过蛇纹石化反应生成(Formisano et al., 2004；Atreya et al., 2007；Fonti and Marzo, 2010)。

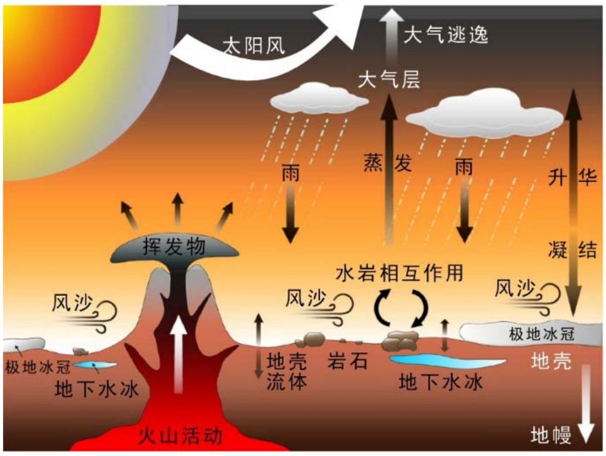

图 7　火星挥发物逃逸示意图（修改自 Hu et al., 2024）。火星火山脱气作用排放出挥发物，并和其他作用共同造成了挥发物的逃逸

Fig.7　Schematic illustration of volatile escape on Mars (modified from Hu et al., 2024). Volatile are released by volcanic degassing on Mars, which together with other processes induced volatile escape

3.1.2　撞击事件　撞击事件会对火星表面环境产生巨大影响，其在火星宜居环境中扮演着双重角色。撞击事件会对火星大气层、地壳结构及潜在生态环境造成严重破坏(MacKinnon and Tanaka, 1989；Lillis et al., 2008；Pan et al., 2023)，直径超过 500 km 的撞击体足以彻底破坏微生物的生存条件(Sleep and Zahnle, 1998)。但同时，撞击会创造利于有机物保存的环境，也可能为火星带来有机分子(Lin et al., 2014；Steele et al., 2016)。例如，Tissint 陨石中观测到的有机碳主要存在于撞击产生的裂隙与冲击熔融脉中，^{13}C 的显著亏损指示着其可能为生物成因，但 Tissint 存在的复杂可溶有机物与碳质球粒陨石中的有机物有着相似的化学和同位素组成，表明其也有可能源自小行星撞击直接输送(Lin et al., 2014；Schmitt-Kopplin et al., 2023)。

如前文所述，火星上的撞击事件持续到了现今。尽管亚马逊纪以来的撞击频率和规模显著降低，但仍有复杂撞击坑形成（图 8）。模拟结果表明，直径大于 7 km 的撞击坑可以在火星上产生热液系统，而直径 30 km 的撞击坑所形成的热液系统可维持超过 6 万年(Abramov and Kring, 2005；Schwenzer and Kring, 2013)。与此同时，复杂撞击坑所产生的裂缝网络将为地下流体运动提供通道(Cockell et al., 2024)，增强近地表与深部水体的联系，这将改善地下宜居环境。此外，亚马逊纪发生的洪水事件及其形成的外流河道(Rodriguez et al., 2015)，也与撞击事件密切相关：撞击致使表层冰融化以及地下水涌出，从而生成大流量径流(Wang et al., 2005；Jones et al., 2011；Weiss et al., 2017)。因此，撞击事件不仅是火星有机物的重要来源之一，还可能通过引发热液活动、水活动及气候效应等来塑造火星近现代的宜居环境演化。

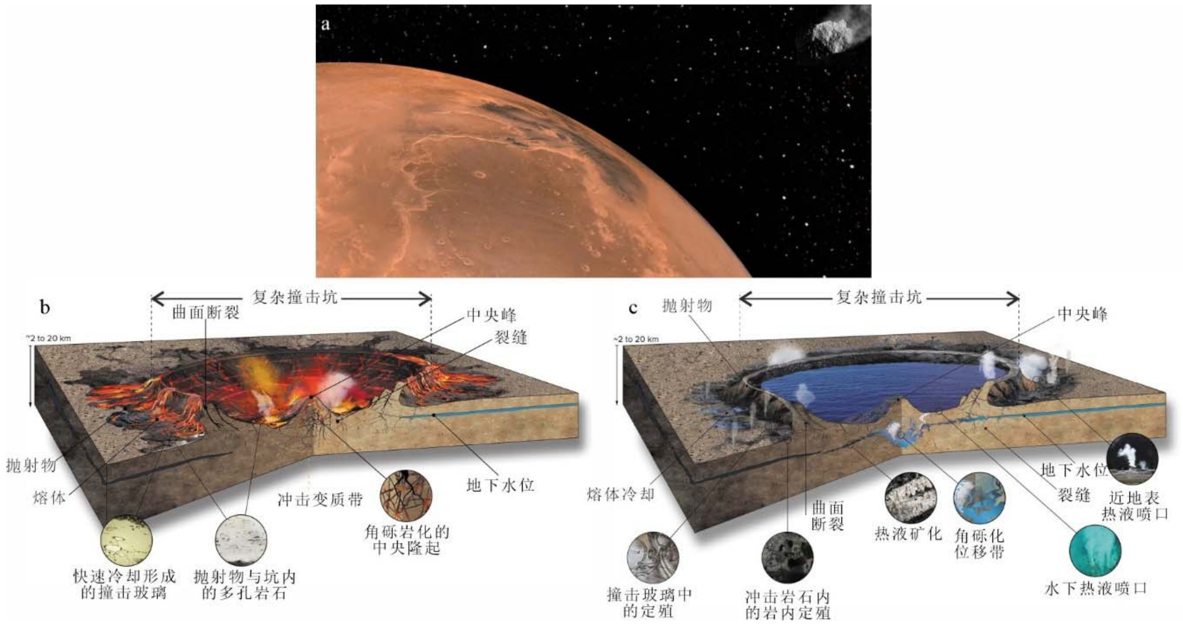

图 8　复杂撞击坑形成过程。（a）撞击示意图，（b）复杂撞击坑形成，坑内部充满了撞击熔融物，并形成裂缝网络，（c）撞击诱发的热液系统，充足条件下可形成湖泊，并生成多种宜居环境。其中，图（b）和（c）参考自 Osinski et al., 2020

Fig.8　The formation process of complex impact craters. (a) Impact schematic diagram, (b) Formation of complex impact craters filled with impact melt and forming a fractures network, (c) hydrothermal system induced by impact, lakes that can be formed under sufficient conditions, and generate multiple habitable environments. Among them, fig. (b) and (c) are referenced from Osinski et al., 2020

3.1.3　冰川活动　在地球上，冰川和冰盖被视为生物群落的一部分(Anesio and Laybourn-Parry, 2012)，其浅层地下存在微生物栖息地，并支持化能自养微生物等群落的生存。现今火星上的冰主要分布在中高纬度，而与地下冰有关的地貌多在中纬度地带(Ulrich et al., 2012；刘正豪等，2024)。极区拥有年龄范围最广泛的沉积地层和最古老的冰，很可能在过去存在宜居区并保留了生命痕迹(Jakosky et al., 2003；Córdoba-Jabonero et al., 2005；Mellon et al., 2024)。然而，火星极地冰层的极端低温将使地下冰稳定存在(Mellon et al., 2004)，这为现今火星极区的宜居性带来了挑战。太阳辐射模拟显示(Khuller et al., 2024)，尽管火星表面遭受的紫外线辐射较地球更为强烈，但火星中纬度出露的冰层中也可能存在辐射宜居区。中纬度出露的冰层可以产生少量融水，这可能使得化能自养微生物（如产甲烷古菌）在其中生存(Williams et al., 2008；Ulrich et al., 2012)。

主要由火星自转轴倾角变化驱动的冰川转移与融化使火星表面周期性地出现宜居环境(Mellon et al., 2024)，其形成的沉积地层为探索火星生命提供了方向。冰川运动通过冻融循环来储存和释放水资源进而调节火星气候，在亚马逊纪的宜居性演化中起到重要作用。

3.1.4　化学风化　火山喷发和撞击事件会产生大量的 H_2、CH_4 和 CO_2(Sholes et al., 2017；Haberle et al., 2019)，由此形成的温暖环境为液态水的存在提供了有利条件，这将为水岩相互作用提供环境基础，并促使岩石发生化学风化。光谱观测表明(Ehlmann et al., 2013；Du et al., 2023)，火星表面广泛分布着由化学风化、热液蚀变和沉积作用形成的粘土矿物（图 9）。多样的粘土矿物指示着不同的地质环境，其不仅可能在生命起源中提供关键化学物质，还具备保存有机物和生物标志物的能力，是衡量火星宜居性的重要指标(Ehlmann et al., 2011；Gainey et al., 2017；Bristow et al., 2018；Du et al., 2023)。

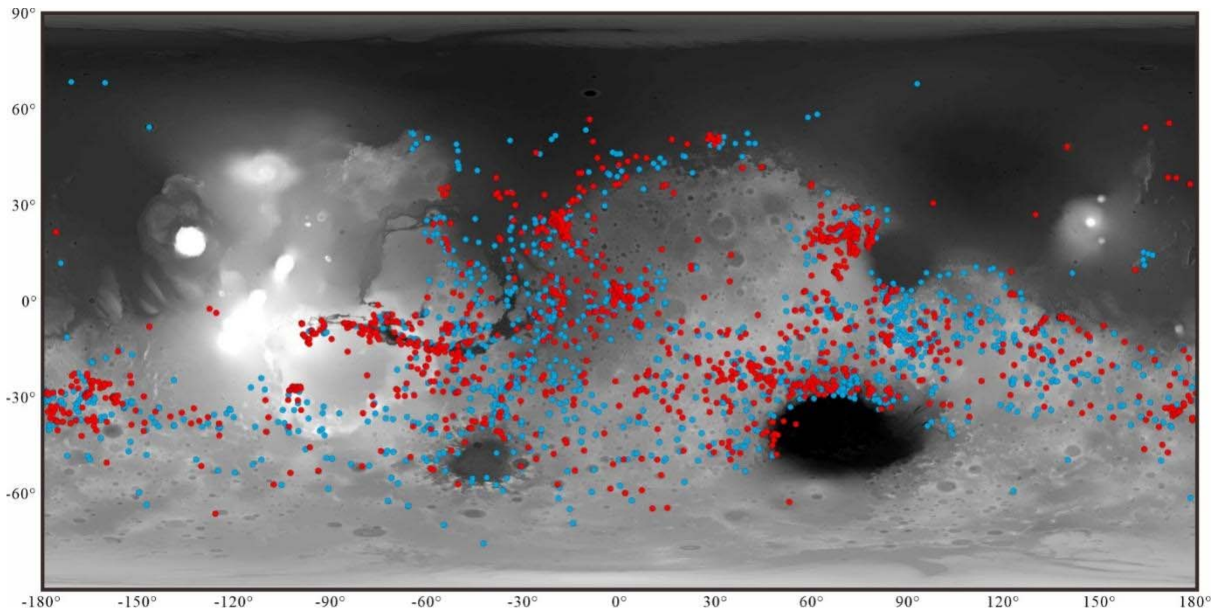

图 9　火星表面粘土矿物分布图。其中蓝色代表铁/镁层状硅酸盐，包括蒙脱石、蛭石和绿泥石等，红色代表含水铝硅酸盐（包括铝蒙脱石，高岭石等）以及水合二氧化硅。矿物数据来自 Carter et al., 2023，底图为 MOLA-HRSE 混合数字高程模型

Fig.9　Distribution of clay minerals on the surface of Mars. Blue represents Fe/Mg phyllosilicate clay, including smectite, vermiculite and chlorite groups, etc. While red represents hydrous aluminosilicates (including Al-smectites, kaolinites, etc.) and hydrated silica. The mineral data is from Carter et al., 2023, with the MOLA-HRSE blended DEM as the base map

与地球类似，火星在数十亿年前经历了从还原环境到氧化环境的全球性氧化还原转变(Liu et al., 2021a)。亚马逊纪以来，火星的化学风化主要表现为缺水、酸性和氧化环境下的风化(Hurowitz and McLennan, 2007)。矿物学分析显示，在一些亚马逊纪撞击坑的撞击熔体中检测到了潜在的自生粘土(Sun and Milliken, 2015)，这表明即使在亚马逊纪，仍存在局部粘土矿物形成的环境。此外，子午线高原西方纪时期的硫酸盐沉积可由冻融循环驱动的化学风化解释(Liu et al., 2024b)，而该过程在亚马逊纪也仍有可能发生。

不可逆的化学风化会加剧火星的干旱程度(Scheller et al., 2021)。在地球上，板块构造促进了水循环，通过化学风化作用进入矿物质中的水最终会通过火山作用释放到大气中(Lammer et al., 2009)。而火星上大多数水合矿物的古老年龄表明(Ehlmann et al., 2011)，类似的水循环在火星并未持续存在。早期火星广泛的化学风化导致地壳水合作用，使水分子封存于矿物质中(Scheller et al., 2021)，而在亚马逊纪，这一效应将使火星水循环进一步减弱。

化学风化在火星近现代的表现较早期显著减弱，过去的 1 ~ 50 Myr 中，火星化学风化速率比地球最慢处（南极）还要慢 1 ~ 4 个数量级(Schröder et al., 2016)。尽管如此，其在局部环境中的持续作用可控制地壳水储量并改变地表矿物学环境，进而影响火星近现代的宜居环境演化。

3.1.5　蛇纹石化和热液系统　蛇纹石化反应通过高还原的橄榄石和富含辉石的岩石与水的交代作用，释放出 H_2 和热能。蛇纹石化反应在早期火星可能十分普遍(Schulte et al., 2006；Tutolo and Tosca, 2023)，南部高地上检测到的与蛇纹石化相关的矿物为其提供了直接证据(Ehlmann et al., 2010；Amador et al., 2018)。在存在地下水的条件下，火山活动(Schulze-Makuch et al., 2007；Skok et al., 2010)、撞击事件(Turner et al., 2016；Carrozzo et al., 2017)、蛇纹石化反应(Lowell and Rona, 2002；Schulte et al., 2006；Chassefière et al., 2016)和放射性热(Ojha et al., 2021)等因素均可驱动火星上的热液循环，形成热液系统。

尽管亚马逊纪以来，火星气候愈发干燥，大气持续流失，但这一时期仍存在蛇纹石化反应和热液活动。

矿物学研究表明，在部分亚马逊纪撞击坑和火山锥体单元内已检测出蛇纹石、绿泥石、蛋白石等与热液活动和蛇纹石化反应相关的矿物(Turner et al., 2016；Brož et al., 2017)。同时对火星 Nakhla 陨石的分析显示，其源岩在火星上经历了两次撞击事件，而约 633 Ma 的首次撞击产生的热液活动，使该陨石发生了低温（150 ~ 200 ℃）水蚀变过程(Borg and Drake, 2005；Bridges and Schwenzer, 2012；Daly et al., 2019)。此外，放射性生热可在无岩浆供热的条件下长期驱动热液系统并维持宜居环境(Ojha et al., 2021)，这也有可能在火星亚马逊纪得到延续。

热液系统对火星天体生物学意义重大，其内部的氧化还原梯度、能量源以及富含生命必需元素的水溶液，为生命生存和前生命化学过程（Prebiotic）提供了适宜环境(Martin et al., 2008；Ojha et al., 2021；罗根明等，2025)。热液环境中磁性矿物的沉淀会影响火星的地壳磁性特征(Shau et al., 1993；Lillis et al., 2008)。生命也可能通过热液活动和水岩反应在火星深处得以维持，并在火星深处保存潜在的生物标志物(Ojha et al., 2020)。近期在火星陨石 ALH 84001 中发现了与矿物碳酸化和蛇纹石化反应相关的有机物，指示了火星有机分子的水岩相互作用来源(Steele et al., 2022)。

3.1.6 大气活动 低层大气过程在调节氢的热逃逸方面发挥着重要作用(Heavens et al., 2018；Yiğit, 2021；Yiğit et al., 2021)（图 10），而原子氢向太空的热逃逸是火星长期水流失的主要机制，其受大气波和尘暴的影响(Jakosky et al., 2018；Yiğit, 2021)。

亚马逊纪以来，尘暴活动对火星大气的动力学和热力学影响显著，其影响范围从地表延伸至热层和电离层(Wu et al., 2020)。2018 年 6 月观测到的全球性尘暴是火星尘暴的典型案例，尘暴期间，火星尘埃不透明度和温度升高(Kass et al., 2020)，低层大气重力波活动受抑制，热层重力波活动显著增加(Kuroda et al., 2020；Yiğit et al., 2021)。ExoMars（Exobiology on Mars）的观测结果显示，尘暴活动与水循环联系紧密。强烈的尘暴使火星低层大气吸热，加速氢向高层大气热逃逸，导致高层大气 H_2O 和 HDO 丰度增加，进而影响高空水冰云(Liuzzi et al., 2020；Neary et al., 2020)。

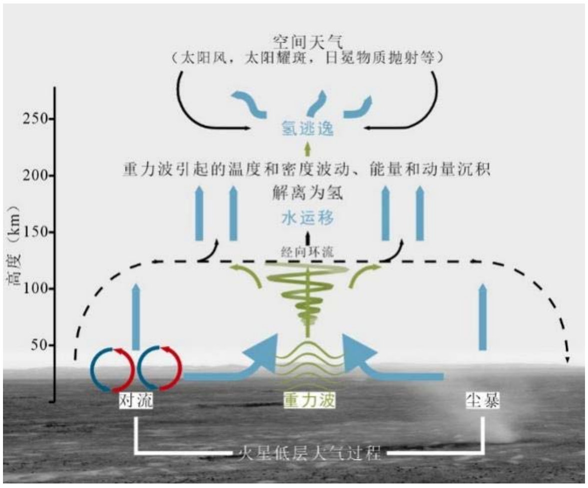

图 10 火星的低层大气过程影响了氢的热逃逸。模式图修改自 Yiğit, 2021，尘暴影像来自勇气号火星车的导航相机（2005 年 7 月），来源：NASA/JPL-Caltech/Texas A&M/Cornell

Fig.10 Martian lower atmospheric processes affect the thermal escape of hydrogen. Schema diagram modified from Yiğit, 2021. The dust storm image was taken by Spirit's navigation camera (July 2005). Credit: NASA/JPL-Caltech/Texas A&M/Cornell

此外，尘暴活动还会控制火星盐类的性质和形成(Mao et al., 2022, 2023)。例如，尘暴活动中发生的静

电放电过程可使火星大气中的 CO_2 固化为碳酸盐(Mao et al., 2023)，而由于持久、活跃的尘暴活动，其 CO_2 的封存量可达到~ 0.56 mbar。

大气逃逸是中性粒子和带电粒子从行星大气层和电离层流失到太空的过程。由于火星缺乏全球性磁场，易受太阳风渗透，太阳风、日冕物质抛射等空间天气效应与火星热层、电离层和散逸层相互作用，加剧了火星大气逃逸，导致大量水损失(Dong et al., 2014；Mayyasi et al., 2018；Yiğit, 2023)。

3.2 火星宜居性评价指标

构建火星宜居性评价指标体系，对寻找生命和未来人类在火星上的探索中具有重要意义。宜居性即天体承载生命的潜力，Cockell(2014)提出能够支持至少一种已知生物活动的环境就是宜居的，其中活动是指包含生存、维持、生长和繁殖等代谢活动。宜居性评价指标体系需要考虑生命形成和活动的核心影响因素。学界普遍认为，水、适宜的物化条件、能量和元素是行星宜居性的关键四要素(Hoehler, 2007；Cockell et al., 2016)。

对于火星来说，其表面存在生命的可能性较低，因为尘暴、辐射以及太阳风等事件会对火星地表或浅地表可能存在的生物环境造成显著破坏(Mancinelli and Klovstad, 2000；Hassler et al., 2014)。相反，火星地下是理想的宜居环境场所(Cockell et al., 2016；Michalski et al., 2018；刘洋等，2021a；史语桐等，2025)，上述作用于表面的事件对地下环境影响有限，可以为潜在生命提供庇护所。同时，火星地壳可能存在深部水冰层并为地下环境提供水源，而火山活动和撞击作用也将提供热源来维持液态水(Westall et al., 2013)。而相比复杂的生命体，微生物可以适应各种极端环境，例如高温、极寒、高酸、高碱、高盐等等(雷婷婷等，2022；庄滢潭等，2022)，它们的存活要求更为宽泛，不需要苛刻的环境条件。早期火星地壳提供了有利的环境，微生物可以在地下生存，而现今的火星是否存在微生物是未知的(Changela et al., 2021；Sauterey et al., 2022)。若火星历史上出现过微生物，它们的活动痕迹（如代谢残留、生命信号分子等）就很有可能会被保存在地下(Westall et al., 2015；罗根明等，2025)。

聚焦火星地下环境和潜在微生物，我们需要重新衡量各要素的权重。首先，微生物具备的强大适应能力，以及地下环境对尘暴、辐射、太阳风等影响的缓冲与隔离，使物化条件对其影响较小；其次，火星具备的生命必需元素（C、H、O、N、P、S，Cockell et al., 2016）显著降低了“元素”这一基本要素的优先级。因此，水和能量是制约地下宜居环境和潜在微生物的关键因子。

水作为生命的溶剂，同时也是能量传输的介质。火山活动所形成的地热环境以及撞击作用所释放的瞬时热能与地下水冰相结合将驱动热液系统，同时蛇纹石化等水岩相互作用也会产生热量。所以，和地下宜居环境及潜在微生物直接相关的要素是水，没有水，其他的影响要素都将缺乏根基(Cockell, 2014)。在此背景下，我们将水作为此评价指标体系的基石，其赋存状态，持续时间将是核心考虑要点。深入研究火星历史上水的存在和活动方式，包括水存在的直接证据、储存方式、水岩相互作用以及火山活动与地下水活动的关系等，是解决火星宜居性问题的关键，也是火星科学和探测的重点研究内容(Xiao, 2023)。

火星存在的种种证据，例如广泛分布的河流地貌(Liu et al., 2021b；Zhao et al., 2021；Shi et al., 2022)、古湖泊(赵健楠和肖龙，2016；Zhao et al., 2020)、水合矿物(Du et al., 2023；Ju et al., 2024)、古海洋遗迹(Di Achille and Hynek, 2010；Xiao et al., 2023a；Wu et al., 2024；Li et al., 2025)等均表明火星历史早期存在有大量的地表液态水。在这种情况下，早期火星存在形成生命的条件。而随着磁场消失(Mittelholz et al., 2020)，太阳风等空间天气效应破坏火星大气层(Yiğit, 2023)，全球干旱化加剧，生命体可能转移至更深层的地下以规避表面事件对其造成的破坏(Westall et al., 2013；Michalski et al., 2018)。火星地表或浅地表的生命可能随

之被破坏消失，但其活动痕迹也有可能会被保存下来，例如在热液、湖泊或古土壤等沉积环境(Westall et al., 2015)。因此，火星宜居性评价指标体系不仅需考虑对生命形成的潜力，也需要将生命保存能力纳入其中。

结合上述认识，我们尝试建立了火星宜居性的评价指标体系（表 1），从水活动强度、能量供给效率、生命形成潜力以及生命保存能力这四个方面来综合评价。其中，水活动强度主要考虑水的赋存状态和持续时间。

表1：火星宜居性评价指标

Table1 The index of habitability assessment on Mars

影响因素	评价指标				依据	参考文献
	水	能量	生命形成	生命保存		
热液系统	强	强	强	强	热液系统能稳定维持液态水，为生命提供基础溶剂。同时可构建持续的氧化还原梯度，供给生命活动所需能量，释放碳、氮、磷等生命必需元素，此外其稳定的环境可有效留存生物标志物。生命形成潜力和保存能力强	(Martin et al., 2008；Ojha et al., 2020；Ojha et al., 2021；罗根明等，2025)
火山活动	中等	强	强	中等	火山喷发过程将释放水和其他挥发物，但持续供水能力有限。火山热结合地下水冰可长期驱动热液系统，具备较高的生态位生成与维持能力，生命形成潜力强。火山活动形成的熔岩管（具温度稳定性、辐射防护能力）、喷气孔（提供物质输送通道）等地形，是保存生命痕迹的理想场所，此外，后期相对低温阶段的矿物沉淀过程也可保存生物标志物，但喷发过程带来的极端高温将破坏局部微环境，使得生物标志物发生降解与转化，因此生命保存能力中等	(Schulze-Makuch et al., 2007；Djokic et al., 2017；Moreras-Marti et al., 2021；Sánchez-García et al., 2023；Tan et al., 2023; Xu et al., 2024；Hadland et al., 2024；佘星阳等，2024)
蛇纹石化	弱	弱	强	强	蛇纹石化将释放 H_2 和能量，形成并维持对液态水存在的有利环境，并驱动热液系统，但同样，蛇纹石化反应在亚马逊纪较为微弱，使得对水的影响和获得的能量通量与时间尺度有限。蛇纹石化反应可促进还原碳化合物生成，同时其产生的碱性热液可提供PH 梯度，生命形成潜力强。此外，与蛇纹石化反应伴随的碳酸盐与粘土等矿物沉淀可高效保存生物标志物，因此生命保存能力强	(Lowell and Rona, 2002；Kelley et al., 2005；Schulte et al., 2006；Chassefière et al., 2016；Amador et al., 2017；Bosak et al., 2021；Steele et al., 2022；Schwander et al., 2023)
冰川活动	中等	——	中等	中等	冰川活动在亚马逊纪非常活跃，其可有效调整水资源分布，使火星表面周期性地出现水活动。当前火星条件下，中纬度冰层可能会产生少量融水，裸露冰层内部可能存在辐射宜居区，并适合光养微生物如蓝藻等生存。同时地下水冰层的存在将提供反应界面，并	(Williams et al., 2008；Pavlov et al., 2012；Ulrich et al., 2012；Khuller et al., 2024；Mellon et al., 2024；Sizemore et

					充当前生命化学反应介质与溶质迁移通道，但低温限制了微生物种群规模与演化潜力，因此生命形成潜力较弱。此外，冰层可屏蔽辐射并保存有机物，但其较依赖冰层厚度，浅表层的有机物将被辐射破坏，生命保存能力中等。	al., 2026)
撞击事件	中等	中等	中等	不利	复杂撞击坑形成时会融化冰层并释放地下水，诱发区域性热液系统，但持续能力依赖其撞击规模。撞击不仅可能为火星带来有机分子，其所产生的裂缝网络也将改善地下宜居环境，利于建立局部生态系统，生命形成潜力总体评为中等。而撞击过程所带来的极端高温、冲击等将破坏地表宜居环境，同时挖掘出来的有机物将经历变质降解，因此不利于生命保存。	(Abramov and Kring, 2005；Schwenzer and Kring, 2013；Montgomery et al., 2016；Steele et al., 2016；Pan et al., 2023；Cockell et al., 2024)
化学风化	不利	——	中等	强	化学风化将液态水封存在矿物中从而降低液态水含量，并加剧干旱程度，但亚马逊纪以来的风化速率极低，对水的影响较弱。其风化产物如粘土矿物可提供高比表面积与反应界面，并可作为催化剂，对前生命化学过程与局部宜居环境具促进意义，生命形成潜力中等。此外，风化产物还具备强吸附性，并以此高效保存有机物，生命保存能力强	(Hazen et al., 2010；Ehlmann et al., 2011；Schröder et al., 2016；Gainey et al., 2017；Scheller et al., 2021；Du et al., 2023；Zhao et al., 2023b)
尘暴活动	不利	——	不利	不利	尘暴过程中，尘埃吸收太阳辐射并加热低层大气，这将加速氢向高层大气的热逃逸，造成地表水损失，同时尘暴等风沙活动将侵蚀、破坏浅表层宜居环境，摧毁可能存在的生命痕迹，对生命形成与保存均产生显著不利影响	(Jakosky et al., 2018；Yiğit, 2021, 2023)
空间天气效应	不利	弱	不利	不利	火星缺乏全球磁场，太阳风、日冕物质抛射等空间天气效应可直接穿透大气，剥离高层大气中的氢原子，使火星在亚马逊纪经历了大规模的水损失，但同时辐射也将产生少量化学能。高能粒子辐射会破坏浅地表矿物结构与有机分子，摧毁宜居微环境，对生命形成与保存构成致命威胁。	(Mayyasi et al., 2018；Tarnas et al., 2018；Yiğit, 2023)

注释：强：持续时间长，强度大，且较稳定；中等：对指标具有贡献度，但存在一定局限性；弱：持续时间短，不稳定，局限性大；不利：总体情况对该指标不利。

如表 1 所示，火星近现代宜居性演化受到多因素动态耦合的调控，火山活动，撞击事件以及蛇纹石化反应通过释放挥发物和能量来增加液态水储量，使火星变暖以维持液态水并驱动热液系统。此外，化学风化、蛇纹石化等水岩相互作用通过矿物封存促进了潜在生命特征的保存。冰川活动通过储存和释放水资源

来动态调节火星气候，并为潜在生命提供保护。尘暴和包括太阳风、日冕物质抛射等在内的空间天气效应则造成了大规模的氢逃逸，并破坏大气层和浅层地表宜居环境。在它们共同作用下，使火星成为了一个寒冷干旱，大气稀薄的行星。尽管如此，亚马逊纪以来的地质活动（火山、撞击、冰川等）仍在影响着地下环境，使其局部可能维持适宜的温压条件、液态水活跃性并提供能量。因此，现今火星地下仍可能具备适合微生物生存的潜在环境，并保留有生物标志物，甚至可能存在延续至今的生命。

4　总结与展望

火星亚马逊纪以来的地质活动主要包括火山活动、撞击作用、水及冰川活动和风沙作用等，这些地质过程对火星的宜居性环境的形成具有重要影响。火山活动释放出的气体和热量，改变了火星的大气组成和温度，并可能为微生物的生存提供了适宜的环境。撞击作用不仅改变了火星表面的地形，还可能带来了水和有机物，为生命的潜在存在创造了条件。冰川运动则通过储存和释放水资源调节了火星的气候，而风蚀过程对火星表面物质的分布和形态进行了重塑。未来的探测应重点关注火星火山活动的演化过程、撞击坑中可能存在的有机物质、浅表层水冰的分布情况以及风蚀痕迹的成因与演变，以进一步了解火星的地质历史和现今的地质动态，从而评估其宜居潜力。

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