

火星水成地貌研究进展

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内容提要:液态水在火星地表的塑造过程中起到了重要的作用,形成了峡谷网、外流河道、古湖泊以及三角洲和冲积扇等多种多样的水成地貌,它们一直是火星探测与研究的热点和焦点。本文对火星水成地貌的探测历史、地形地貌特征、时空分布等方面的研究进展进行总结,探讨水成地貌对火星气候演化及天体生物学研究的指示意义。在此基础上,提出当前火星水成地貌研究存在的问题,认为需要在火星水成地貌的水源类型、水成地貌所指示的火星水环境特征、亚马逊纪水成地貌的成因、火星水成地貌与我国柴达木盆地地貌的类比等方面开展进一步研究,为更深入的认识火星水成地貌,了解火星气候变化及宜居性提供支持。

关键词:火星;水成地貌;河道;湖泊;古气候;宜居性

火星是太阳系内与地球最为相似的行星。当前的火星是一个寒冷的沙漠星球,表面温度在 $-123\sim 27^{\circ}\text{C}$ 之间变化(Carr, 2006)。火星拥有稀薄的大气层,大气压不及地球的百分之一(平均约 630 Pa),大气主要成分为二氧化碳(约占 95.3%)(de Pater et al., 2015)。目前在火星表面未发现液态水的活动,但是大量干涸的峡谷、古湖泊盆地、三角洲等水成地貌可能指示了火星表面曾广泛存在液态水。这些水成地貌记录了火星地质历史时期的气候环境信息,对它们开展详细的研究,对于揭示火星的地质演化历史及气候变化特征具有重要意义。

另一方面,火星也是当前国际深空探测的热点,美国、欧盟、俄罗斯、印度、阿联酋等国家或组织都正在或计划实施火星探测任务(Zhao Yuyan et al., 2020)。我国于2020年发射了“天问一号”火星探测器,并于2021年5月15日成功实施软着陆,一次性完成了对火星的环绕、着陆和巡视探测(Ye Peijian et al., 2017; Li Chunlai et al., 2018; Geng Yan et al., 2018; Wan et al., 2020)。这些探测任务的重要目标之一是探索火星表面的水活动记录及宜居

性,而水成地貌的研究是达到这一目标的重要途径。因此,有必要对当前火星水成地貌的探测历史、研究现状及存在的问题进行分析,为未来火星任务中探测目标的选择及对火星生命和宜居环境的搜寻提供支持。

1 火星水成地貌的探测与研究历史

1971年发射的“水手9号(Mariner 9)”是第一个成功环绕火星的探测器,其最重要的发现之一即拍摄到了火星表面类似地球峡谷和河网的地貌(Masursky, 1973)。随后,1975年发射的“海盗1号(Viking 1)”和“海盗2号(Viking 2)”获得了更高分辨率(每像素约 200 m)的火星全球影像,发现上述地貌在火星表面广泛分布。这些探测结果引发了人们对地貌成因的探索热潮(Cabrol et al., 2010),除流水作用外,早期的研究者也提出了构造运动(Schumm, 1974)、冰川作用(Lucchitta, 1980, 1982)、熔岩流侵蚀(Greeley, 1973; Carr, 1974)、二氧化碳水合物解离(Milton, 1974; Yung et al., 1978)等多种成因假说。但是,根据探测器获得的火

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星物理参数及大气观测数据,结合初步的气候模型分析结果,这些类似河网的地貌最可能是由液态水的活动形成,进而推测火星地质历史早期可能存在温暖湿润的气候(Sagan et al., 1973; Toon, 1980; Baker et al., 1991; McKay et al., 1991; Clifford, 1993; Carr, 1995; Kasting, 1997)。

从 20 世纪末至今,国际火星探测掀起了新的高潮,以“火星勘测轨道飞行器(Mars Reconnaissance Orbiter, MRO)”为代表的一系列火星环绕器及以“好奇号(Curiosity)”为代表的火星着陆巡视器获得了大量高分辨率的遥感影像、光谱及原位探测数据。通过地貌学和沉积学的详细解析(Grant, 2000; Mangold et al., 2004; Erkeling et al., 2010; Warner et al., 2013)、矿物成分和岩石类型的遥感和原位分析(Wray et al., 2009; Carter et al., 2013; Fraeman et al., 2013; Williams et al., 2013a),都有力证明了火星表面的类河网地貌主要由液态水的活动形成,同时,也有更为多样的水成地貌被识别和研究。

2 火星水成地貌的主要类型及其地质特征

火星表面存在多种可能与液态水的活动相关的地貌,如峡谷网(valley network)、外流河道(outflow channel)、古湖泊盆地、冲沟、复现性斜坡纹(recurring slope lineae)等。但是,其中部分地貌的成因尚存在较大的争议,可能并非由液态水的活动形成。例如,Diniega et al. (2013)开展了实验和模拟,结合对火星冲沟影像的分析,提出火星冲沟的形成更可能与干冰的升华过程相关;Dundas(2020)综合分析了火星遥感影像、“好奇号”与“机遇号(Opportunity)”等火星车数据,并开展了地球表面相似地貌的类比研究,认为复现性斜坡纹的形成可能与风力作用下的颗粒流有关。因此,本文暂不对这些争议较大的地貌进行讨论,此处主要介绍目前基本确认的几种水成地貌的地质特征。

2.1 峡谷网

峡谷网是火星表面蜿蜒、狭长且常发育有分支的线状凹陷地貌,它们与地球表面的水系相似(图 1)。单条峡谷的宽度多在 1~4 km 之间,长度可超过 1000 km (Mars Channel Working Group, 1983)。在横截面上,火星峡谷网通常表现出从上游的 V 形到下游的 U 形甚至矩形的转变。但峡谷网的横截面形态很容易受到后期改造作用的影响而显

示出多样性。火星峡谷网的深度在小于 1 m 到大于 400 m 的较大范围内变化,但是大多数峡谷网的深度在 50~200 m 之间,且通常在较长的距离内能保持深度的相对恒定(Williams et al., 2001)。

火星峡谷网具有多种多样的水系形态,如放射状、树枝状、格状、平行状等(Mars Channel Working Group, 1983)。尽管有较为复杂的树枝状水系存在,但火星峡谷网的总体发育程度仍不成熟(Carr, 2006)。Alemanno et al. (2018)研究了火星峡谷网的形态学,并分为典型的树枝状峡谷网、纵向延伸的峡谷网、孤立峡谷以及与大峡谷或火山相关的峡谷网四类。除此之外,火星表面还存在一种特殊的峡谷网,不同于一般峡谷网的负地貌,它们具有弯曲的脊状形貌特征,是由古河床经历差异风化发生地形倒转而形成,因此也被称为倒转河道(inverted channel;图 1c)。具体而言,原始河床底部的物质可能通过化学胶结作用、固结成岩、或被相对坚硬的物质(如砾石或后期充填的熔岩)覆盖而变得更加难以侵蚀,当较易风化的河岸被侵蚀后,原始的河床将变成弯曲而凸起的脊状地貌(Pain et al., 2007; Burr et al., 2009; Williams et al., 2013b; Zaki et al., 2018; Zhao Jiannan et al., 2021)。目前,已经在火星表面发现了 200 多条倒转河道(Williams et al., 2007, 2013b; Burr et al., 2010; Lefort et al., 2012; Liu Zhenghao et al., 2021)。

峡谷网主要分布在火星南部高原(图 2),在北部平原区特别是 Elysium 火山区附近也存在少量峡谷网。目前,已经在火星表面识别出约 40 万条峡谷网分支,总长度超过 77 万 km (Alemanno et al., 2018)。但是,这些峡谷网的分布并不均匀,在 Tharsis 高原、Arabia 高地西部以及 Hellas 盆地西部分布较为稀疏(图 2)。同时,峡谷网的长度也与其分布存在相关性,例如发育在地形坡度相对平缓的 Cimmeria 高地和 Sirenum 高地的峡谷网一般不超过数百千米,但在 Hellas 和 Argyre 盆地以及 Acidalia 平原周围等地势高差较大的区域的峡谷网长度可超过 1000 km。

关于火星峡谷网的成因,目前的主流观点包括地表水的侵蚀及地下水的潜蚀作用(Carr, 2006)。一般认为,具有树枝状水系形态的峡谷网(图 1a)主要是由降水形成的地表径流侵蚀而成,而具有圆弧形的源头、近似矩形的河谷横截面形态的峡谷网(图 1b)可能主要由地下水形成(Irwin et al., 2002; Harrison et al., 2005; Howard et al., 2005)。但

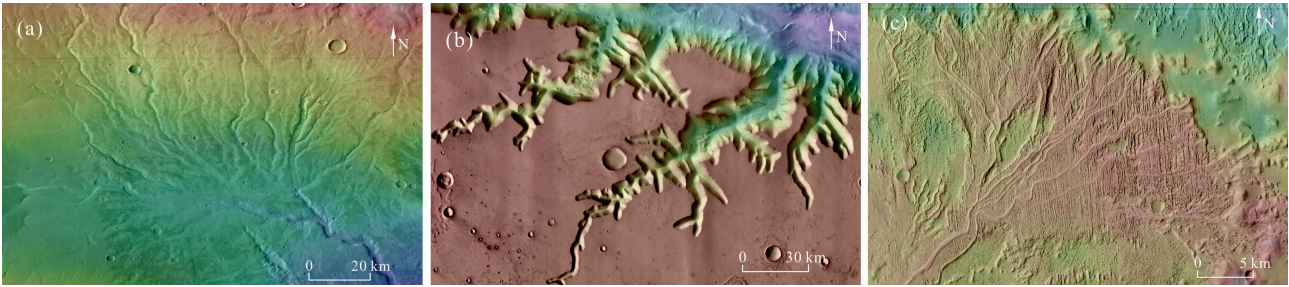


图 1 火星表面的峡谷网和倒转河道

Fig. 1 Martian valley networks and inverted channels

(a) —典型的树枝状峡谷网(中心坐标 92. 6°W, 42. 5°S), 图为火星轨道器激光高度计(MOLA)彩色地形图叠加在背景相机(CTX)影像上; (b) —具有圆弧状源头的峡谷网(中心坐标 84. 5°E, 8. 3°S), 图为 MOLA 彩色地形图叠加在火星奥德赛热辐射成像系统(THEMIS)日间影像上; (c) —发育在火星扇状沉积上的脊状倒转河道(中心坐标 151. 4°E, 6. 2°S), 图为 MOLA 彩色地形图叠加在 CTX 影像上; 各图中红色代表高程较高, 蓝绿色高程较低

(a) —A typical dendritic valley network (central coordinates 92. 6°W, 42. 5°S), the image is Mars Orbiter Laser Altimeter (MOLA) colored topographic map overlaid on Context Camera (CTX) mosaics; (b) —a valley network with amphitheater-shaped headwaters (central coordinates 84. 5°E, 8. 3°S), the image is MOLA colored topographic map overlaid on Mars Odyssey Thermal Emission Imaging System (THEMIS) daytime mosaics; (c) —ridge-like inverted channels developed on Martian fan deposits (central coordinates 151. 4°E, 6. 2°S), the image is MOLA colored topographic map overlaid on CTX mosaics; the red color represents higher elevations while the green and blue colors represent lower elevations

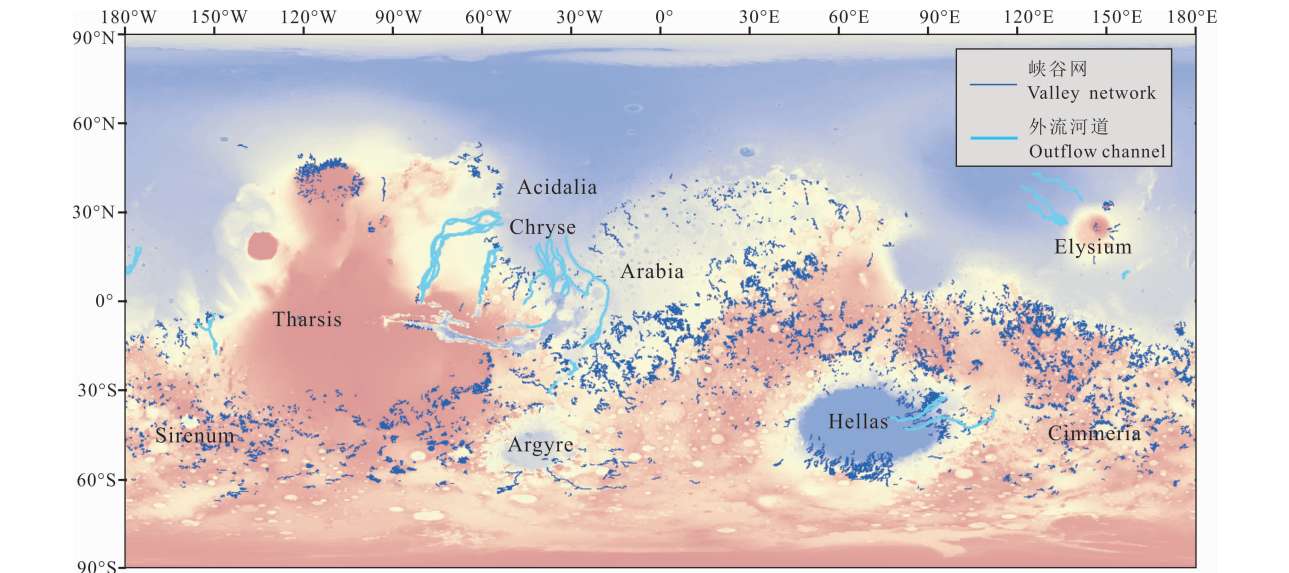


图 2 火星峡谷网及外流河道分布图(据 Carr, 2006; Alemanno et al. , 2018 修改)

Fig. 2 Distribution of Martian valley networks and outflow channels (modified from Carr, 2006; Alemanno et al. , 2018)
底图为 MOLA 彩色地形图; 图中红色代表高程较高, 蓝色高程较低

The background map is MOLA colored topographic map; the red color represents higher elevations
while the green and blue colors represent lower elevations

是,对于火星峡谷网的水源特征,目前依然存在争议,还有待于进一步的研究(见 5. 1 节)。

2. 2 外流河道

外流河道是火星表面主要由爆发性洪水侵蚀形成的大型槽状河道(图 3)。与峡谷网相比,外流河道支流较少,弯曲度相对较小,但具有更大的深度

(可达数千米)和宽度(可达几十千米至几百千米)(Carr, 2006)。例如位于火星 Lunae 高原的 Kasei 河谷的宽度可达 400 km,深度可达 2. 5 km,长度约 3000 km。外流河道通常发源于混沌地貌区(chaotic terrain;图 3a)或大型的地表裂陷(图 3b),并可据此分为混沌发源型(chaos-sourced)和裂隙发

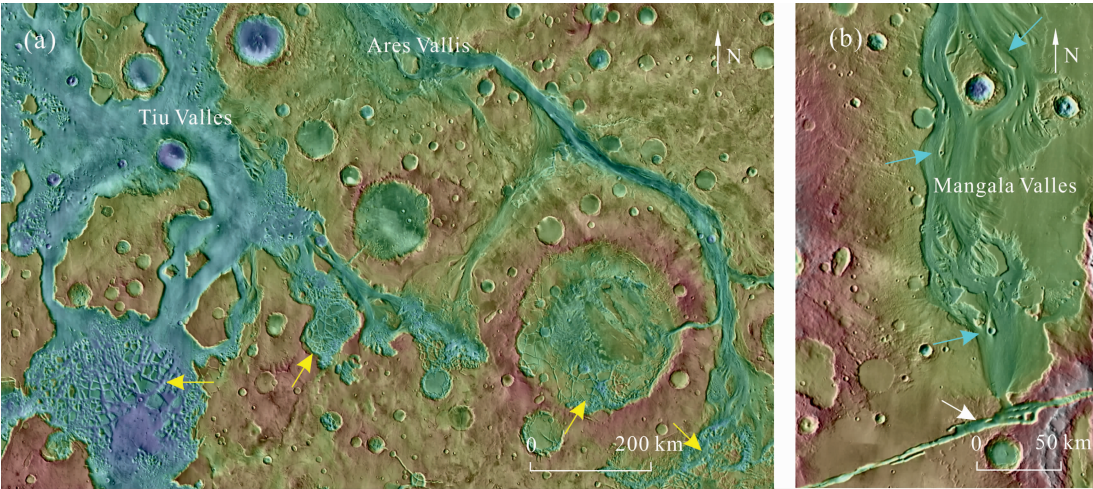


图 3 火星表面典型的外流河道

Fig. 3 Typical Martian outflow channels

(a)—Tiu 和 Ares 河谷(中心坐标 28.0°W,4.8°S)及其源头附近的混沌地貌(黄色箭头);(b)—Mangala 河谷(中心坐标 150.1°W,16.2°S)中的流线型岛屿(蓝色箭头)及其源头处的断裂构造(白色箭头);各图中红色代表高程较高,蓝绿色高程较低;图像均为 MOLA 彩色地形图叠加在 THEMIS 日间影像上

(a)—Chaotic terrain (yellow arrows) near the headwaters of Tiu Valles and Ares Vallis (central coordinates 28.0°W,4.8°S);(b)—streamlined islands (blue arrows) and the fossae (white arrow) near the headwater of Mangala Valles (central coordinates 150.1°W,16.2°S); the red color represents higher elevations while the green and blue colors represent lower elevations; the images are MOLA colorized topographic map overlaid on THEMIS mosaics

源型(fissure-sourced)两类(Carr et al., 2010)。它们一般在源头处即具有与下游河道相近的宽度,而深度则从源头至下游逐渐变浅,河床上常可见纵向的沟槽或脊线以及流线型岛屿(图 3;Carr, 1995, 2006)。

火星上的外流河道主要分布在 Chryse 平原周边区域、Hellas 盆地周围以及 Tharsis 和 Elysium 火山区附近(图 2)。其中,Chryse 平原周边分布有火星表面规模最大的外流河道群,发育有多条长度在 1000 km 以上的外流河道,包括 Tiu 河谷、Kasei 河谷、Maja 河谷以及 Ares 河谷等。它们主要为混沌发源型,源头位于水手大峡谷附近。

关于外流河道的成因,虽然 Leverington(2004)提出部分外流河道具有与月球表面的月溪相似的地貌特征,如突兀出现的源头、较小的弯曲度、河道内有类似熔岩阶地的地貌、源头与熔岩流的源头一致等,可能是由熔岩流动形成,但目前更多的证据表明,外流河道是由爆发性的洪水形成。例如,外流河道具有明显的分流复合现象,河道中央一般存在流线型岛屿,这些都与地球上洪水形成的地貌相似(Carr, 2006; Xiao Long, 2013)。外流河道一般具有突兀出现的源头,这说明它们不是由降水导致的地表流水形成,而是由大量的液态水突然释放所致,

例如构造破裂导致的地下含水层内水的突然释放(Ghatan et al., 2005),湖泊突然泄水(Harrison et al., 2008),或是岩墙侵入导致冰冻层的融化(Wilson et al., 2004; Hovius et al., 2008)。对 Mangala 河谷(图 3b)的模拟研究表明,其峰值流量可达 $10^7 \sim 10^8 \text{ m}^3/\text{s}$ (Ghatan et al., 2005)。

2.3 古湖泊盆地

火星表面广泛分布的峡谷网指示了液态水曾经存在,当水在低洼处汇集,即可形成湖泊。当前,主要根据有峡谷连通的洼地(多为撞击坑)来识别古湖泊。同时,三角洲、层状沉积等沉积地貌也是指示古湖泊存在的重要证据(Zhao Jiannan et al., 2016, 2020)。前人已经对火星古湖泊开展了多次全球性的识别和调查。其中,Cabrol et al. (1999)利用“海盗号”探测器获得的影像识别了 179 个撞击坑古湖泊;Fassett et al. (2008)利用较高分辨率的影像和高程数据,重新对火星表面同时具有水的流入和流出峡谷的古湖泊进行了调查,共识别出 210 个古湖泊;Goudge et al. (2012, 2015)在火星表面识别了超过 400 个古湖泊,它们的直径从几千米到数百千米不等;笔者也通过对更高分辨率影像的分析,提出火星表面的古湖泊可达近千个(Zhao Jiannan, 2017)。根据这些古湖泊盆地所反映的水动力学体

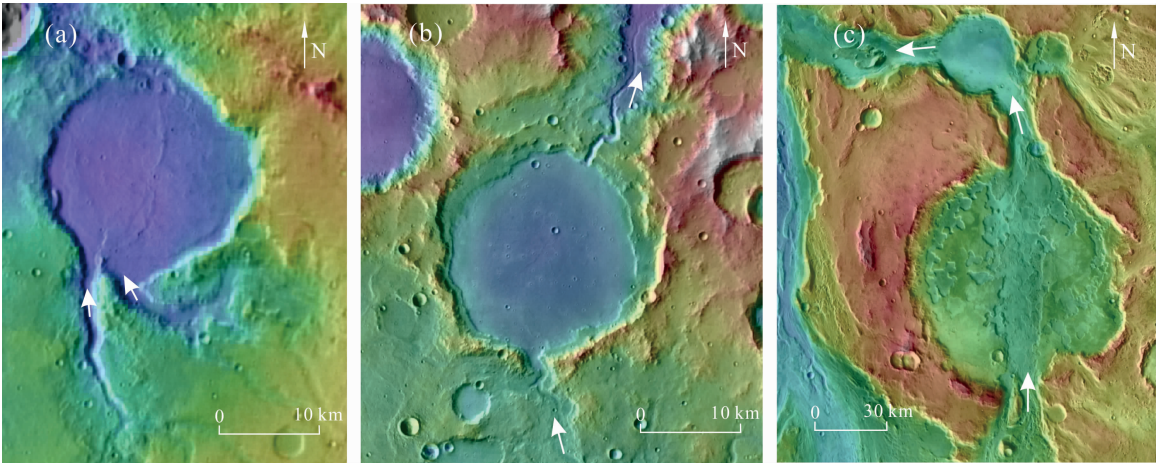


图 4 不同类型的火星古湖泊

Fig. 4 Different types of Martian paleolakes

(a) — 封闭系统古湖泊 (中心坐标 174.8°E, 18.6°S); (b) — 开放系统古湖泊 (中心坐标 174.8°W, 14.6°S); (c) — 湖泊链系统 (中心坐标 14.4°W, 3.5°N); 各图中红色代表高程较高, 蓝绿色高程较低; 图像均为 MOLA 彩色地形图叠加在 THEMIS 日间影像上; 图中白色箭头指示水流方向

(a) — A closed-basin lake centered at 174.8°E, 18.6°S; (b) — an open-basin lake centered at 174.8°W, 14.6°S; (c) — lake chains centered at 14.4°W, 3.5°N; the red color represents higher elevations while the green and blue colors represent lower elevations; the images are MOLA colorized topographic map overlaid on THEMIS mosaics; white arrows indicate flow directions

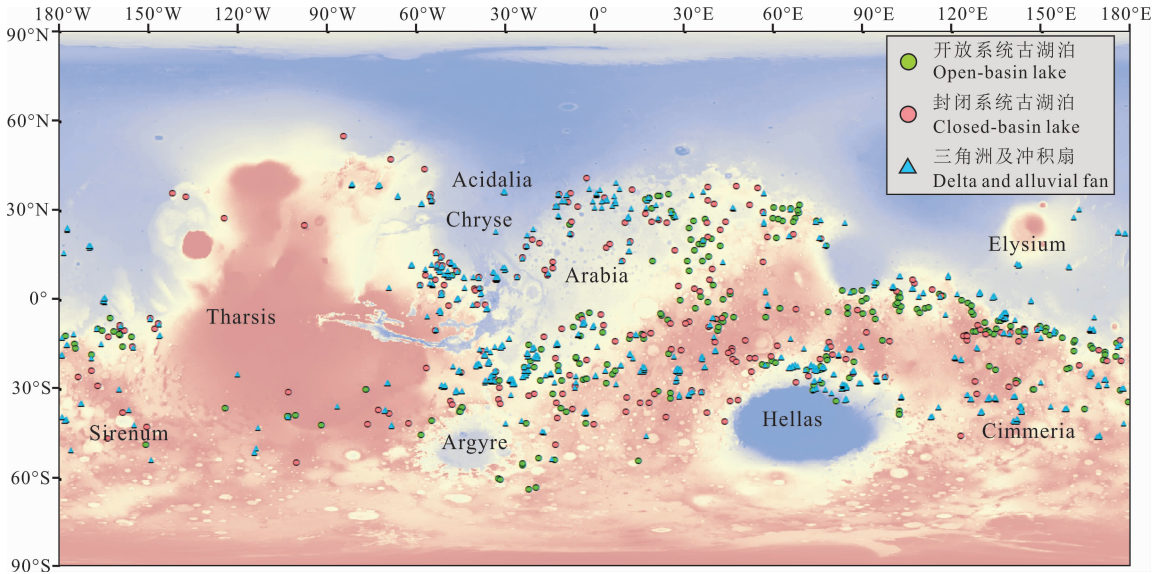


图 5 火星古湖泊及水成扇状沉积分布图(据 Goudge et al. , 2015; Wilson et al. , 2021 修改)

Fig. 5 Distribution of Martian paleolakes, deltas and alluvial fans (modified from Goudge et al. , 2015; Wilson et al. , 2021)

底图为 MOLA 彩色地形图; 图中红色代表高程较高, 蓝色高程较低

The background map is MOLA colorized topographic map; the red color represents higher elevations while the green and blue colors represent lower elevations

系, 可将古湖泊分为三类(图 4): 封闭系统古湖泊、开放系统古湖泊以及湖泊链系统(Cabrol et al. , 1999)。封闭系统(图 4a)是指只有水流入的通道, 而未发现流出通道的古湖泊系统; 开放系统(图 4b)是指同时具有水流入和流出通道的古湖泊系统; 湖泊链系统(图 4c)则是由一系列古湖泊通过一个或

多个峡谷相连, 构成一整套湖泊系统, 而位于该系统最末端的湖泊可能是开放或封闭系统。

火星古湖泊主要分布在南部高原, 其中约 70% 的古湖泊位于南北纬 30° 之间(Goudge et al. , 2015)。由火星古湖泊的分布图(图 5)可知, 古湖泊盆地在火星南北二分性边界附近较为集中, 可能是

由于此区域有大量峡谷网和外流河道发育,为古湖泊提供了充足的水源供给。相比之下,在 Tharsis 地区及 Hellas 盆地的东北及西南部,由于火山活动较为频繁,熔岩流覆盖了大片区域,古湖泊盆地也相对较少。

除了撞击坑内发育的湖泊,火星表面也存在坑间盆地湖泊、火山口湖泊、构造湖泊等多种类型的湖泊(Cabrol et al., 2010)。这些湖泊干涸之后,可能经历多种后期改造作用,如熔岩流充填、冰川活动、风力作用的堆积与侵蚀等,因此火星古湖泊盆地内保存了从早期的水成沉积到后期改造这一全过程的地质记录,是研究火星地质演化的窗口,一直是火星探测与科学研究的热点。

2.4 冲积扇与三角洲

冲积扇和三角洲是水携带沉积物从流域盆地进入平坦开阔区域后,由于水流速突然降低而形成的水成扇状沉积地貌(Plummer et al., 2016)。其中冲积扇一般形成于无水的山前平原或盆地,而三角洲形成于稳定水体中(Nemec et al., 1988; Di Achille et al., 2010; Goudge et al., 2017)。火星冲积扇(图 6a)和三角洲(图 6b)在整体形貌上与地球相似。Cabrol et al. (2001)在火星表面识别出 75 处湖相三角洲,并将其分为扇状、狭长状和朵状三大类。Morgan et al. (2018)在火星表面识别出 84 处独特的阶梯状三角洲,它们被认为是在湖泊盆地的水面不断上升的过程中沉积而形成(de Villiers et al., 2013)。利用高分辨率的影像和高程数据,前人对扇状沉积的形貌进行了测量,结果显示,冲积扇的规模为百米到千米尺度不等,平均坡度约为 4°,其剖面形态多呈下凹状(Moore et al., 2005; Kraal et al., 2008; Williams et al., 2008; Kleinhans, 2010; Morgan et al., 2018);三角洲的大小多在千米尺度,一般具有较低的表面坡度(约 1°~2°),但阶梯状三角洲的坡度可达 7°以上,剖面形态为上凸或下凹(Di Achille et al., 2010; de Villiers et al., 2013; Morgan et al., 2018)。

火星冲积扇和三角洲均呈扇状,两者在形貌上易于混淆,最为可靠的区分冲积扇与三角洲的标志为地层沉积结构。类似地球,不同于冲积扇,三角洲形成于稳定水体,其在地层上具有典型的三层结构:水平至近水平的顶积层、陡峭的前积层、水平至近水平的底积层。因而如果为三角洲,则应在顶积层和前积层以及前积层和底积层间发现两处地层倾角的陡变(Blair et al., 1994; Goudge et al., 2017;

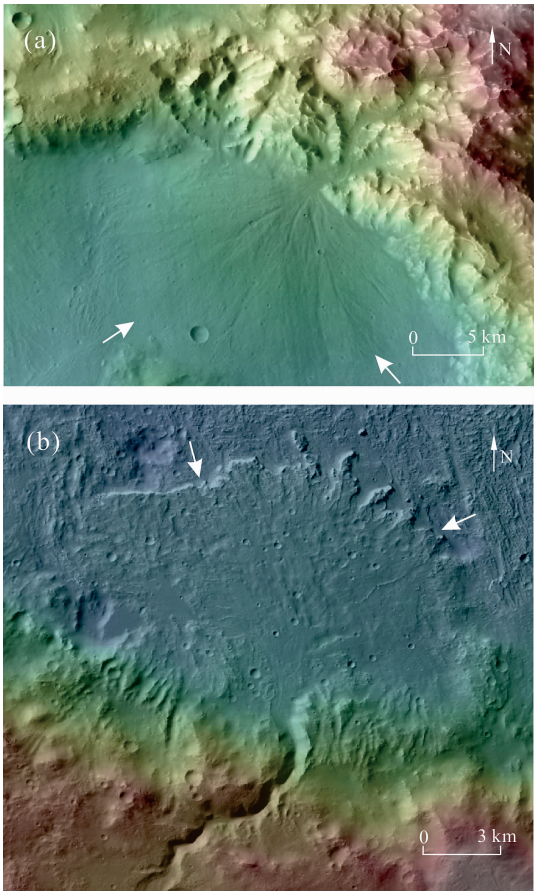


图 6 火星冲积扇(a,中心坐标 74.46°E,22.73°S)与三角洲(b,中心坐标 83.08°E,29.07°S)

Fig. 6 Typical Martian alluvial fan (a, central coordinates 74.46°E, 22.73°S) and delta (b, central coordinates 83.08°E, 29.07°S)

各图中红色代表高程较高,蓝绿色高程较低,图中白色箭头指示冲积扇或三角洲的边缘;图像均为 MOLA 高程图叠加在 CTX 影像上

The red color represents higher elevations while the green and blue colors represent lower elevations; white arrows denote the margin of the fans; the images are MOLA colored topographic map overlaid on CTX mosaics

Hughes et al., 2019)。然而,如此精细的分析需要依赖于“高分辨率成像科学实验装置(HiRISE)”的极高分辨率影像以及火星车相机的影像,但目前这些影像的覆盖率均较低,因此关于火星三角洲的判断仍在进一步研究中。

近年来,对火星水成扇状沉积的识别结果表明,冲积扇和三角洲在火星南部高原上广泛分布且与纬度具有较强的相关性(图 5)。其中,冲积扇多分布于二分性边界附近(0°N~10°N)以及海拔较高的 10°S~30°S,而三角洲则主要分布于海拔较低的 0°N~40°N 且在 0°S~30°S 也有部分分布(Wilson et

al., 2021)。此外,Di Achille et al. (2010)对位于火星二分性边界附近的三角洲进行了识别和研究,并认为它们的分布指示了火星北部平原可能曾为古海洋。

3 火星水成地貌的活动历史

对水成地貌形成时代的约束,主要依靠对地层交切关系的判断以及对水成地貌及其所在地质单元的撞击坑统计定年。撞击坑统计法的全称为“撞击坑大小-频率分布定年法”,它是国际行星科学领域广泛应用的行星表面年龄研究方法。其依据撞击作用总体表现为随着时间的推移,天体表面撞击坑的大小和数量不断减小的规律,通过对撞击坑的大小和频率分布进行统计,并与年代学曲线进行拟合,即可获得天体表面的绝对模式年龄(Ivanov, 2001; Neukum et al., 2001; Michael et al., 2010; Zhao Jiannan et al., 2013)。

在峡谷网年龄的研究上,可通过分析峡谷网所流经的地质单元的时代以为峡谷网的形成年龄提供约束。目前,不同的填图结果得到的峡谷网年龄略有不同,但总体特征一致。根据Carr et al. (1997)的水系分布图,90%的峡谷网分布在诺亚纪地质单元中。Hynek et al. (2010)的结果表明,91%的峡谷网分布在诺亚纪单元,6%分布在西方纪单元,剩余3%则分布在亚马逊纪地质单元内。Alemanno et al. (2018)的研究结果则显示有高达94%的峡谷网分布在诺亚纪地质单元。总体而言,火星峡谷网的形成时间主要是诺亚纪,也有部分延伸至西方纪。

古湖泊及其内部发育的三角洲和冲积扇等水成地貌一般与峡谷网相连,故具有与峡谷网相对一致的活动年龄。Fassett et al. (2008)利用火星高分辨率遥感影像数据,采用带缓冲区的撞击坑统计法,对与火星古湖泊相连的峡谷网的年龄进行了研究,得到它们的平均年龄为3.53 Ga(根据Hartmann定年方法)或3.75 Ga(根据Neukum定年方法),因而判定火星古湖泊在诺亚纪与西方纪交界时期逐步干涸。此外,也可通过对古湖泊盆地内部的原始沉积物单元如层状沉积、三角洲沉积等进行定年以约束古湖泊干涸的时代。Zhao Jiannan et al. (2020)对Hellas盆地西北部区域部分古湖泊的湖底沉积物单元进行了定年,得到了3.64~3.54 Ga的定年结果,指示着该区域古湖泊主要在诺亚纪与西方纪过渡时期干涸。

值得注意的是,在相对干旱寒冷的亚马逊纪,也

可能存在液态水的活动,并形成湖泊和冲积扇等水成地貌。Howard et al. (2011)提出火星Newton和Gorgonum盆地可能在西方纪和亚马逊纪交界时期存在湖泊活动。Wilson et al. (2016)通过对河道特征的研究,在火星Arabia高地地区发现了近10个可能活动于亚马逊纪的古湖泊。Grant et al. (2019)对“好奇号”着陆点Gale撞击坑内冲积扇的定年结果表明,部分冲积扇的年龄可能小于2 Ga,并认为在亚马逊纪Gale撞击坑内也可能有晚期的水活动。

外流河道较峡谷网更宽,可以在河床上直接实施撞击坑统计定年获得外流河道的活动时代。但需要注意的是,外流河道可能经历后期的改造作用,如熔岩流的充填,因而必须利用高分辨率影像和光谱数据,在对河床物质加以识别和判断的基础上,确认是否能通过撞击坑统计获得有效的外流河道活动年代。目前,对外流河道开展的地质填图表明,它们主要活动于西方纪,并以晚西方世为主(Kreslavsky et al., 2002; Tanaka et al., 2005),但是也存在亚马逊纪的外流河道,如Rodriguez et al. (2015)提出流入Chryse平原的部分外流河道可能存在多次流水活动,且主要的活动时间为亚马逊纪,并在中亚马逊世达到峰值。

总体而言,火星表面的水成地貌主要形成于诺亚纪并延伸至西方纪,与水成矿物的形成时代较为吻合(图7; Bibring et al., 2006; Ehlmann et al., 2011),而亚马逊纪水成地貌较少,这也反映了火星气候及液态水环境的变化。

4 火星水成地貌的气候及天体生物学意义

火星气候演化及宜居性是火星科学的重大研究课题,它们都与水的活动密切相关,因此,对火星表面水活动的记录——水成地貌的详细解析可为该课题的研究提供重要线索。

当前,对火星的早期气候条件仍存在较大的争议。一方面,火星表面广泛存在具有树枝状水系形态的峡谷网、不同类型的古湖泊、三角洲和冲积扇等水成地貌,火星车的原位探测也证实了河流和湖泊的存在,结合大量出露的黏土矿物及风化剖面,共同指示了火星早期可能存在温暖湿润的气候条件(Craddock et al., 2002; Ansan et al., 2006; Baker, 2006; Bibring et al., 2006; Williams et al., 2013a; Carter et al., 2015; Grotzinger et al.,

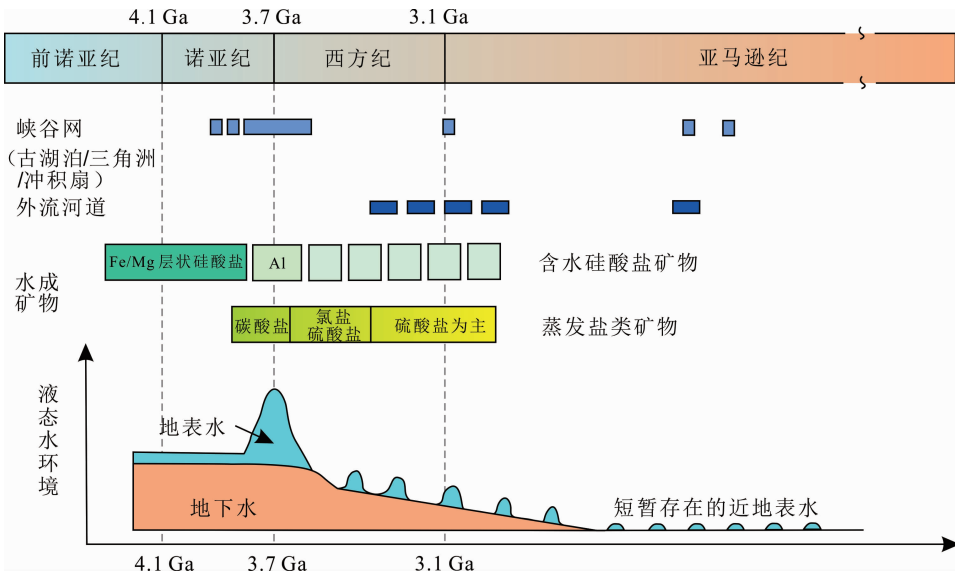


图 7 火星水活动历史(据 Ehlmann et al. , 2011 修改)

Fig. 7 Aqueous history of Mars (modified from Ehlmann et al. , 2011)

2015; Ramirez et al. , 2018; Liu et al. , 2021)。同时,对峡谷网和古湖泊的定年结果显示,它们主要在诺亚纪和西方纪交界时期停止活动,指示了从诺亚纪进入西方纪,火星气候发生了重大变化,可能从温暖湿润变为寒冷干旱,不再适合地表水的存在(Fassett et al. , 2008)。但另一方面,也有观测结果支持火星早期存在寒冷干燥的气候。例如,火星峡谷网发育不成熟,且通常在下游保持相对恒定的宽度,而地球表面的河流则在下游变得更宽、更深(Carr, 2006; Grau Galofre et al. , 2020);火星的峡谷网存在一些弯曲度较小、源头突然出现的小规模浅支流,它们往往具有 U 形的横截面,可能表明其形成于地下水的潜蚀作用或冰川侵蚀作用(Laity et al. , 1985; Malin et al. , 1999),指示相对寒冷的气候条件。同时,在火星早期具有稠密的 CO₂ 大气、低太阳能的环境下,气候模型无法模拟出温暖湿润的条件,由此认为火星早期应该是寒冷干旱的(Forget et al. , 2013; Wordsworth et al. , 2013)。

为解决这两种气候模式之间的矛盾,温暖干旱(Ramirez et al. , 2018; Seybold et al. , 2018)、寒冷湿润(Fairén, 2010; Kamada et al. , 2020)、周期性温暖湿润(Halevy et al. , 2014; Cang et al. , 2019)等其他气候模式也被相继提出,但尚未有任何一种气候模式能够完美解释火星地表多样的水成地貌特征。因而,研究者也提出火星早期气候可能存在区域差异性(Fassett et al. , 2008; Zhao Jiannan et al. , 2020),例如 Fassett et al. (2008)对火星古湖泊流域面积及湖泊面积的对比研究发现,火星 40°W

至 80°E 之间的区域具有较为湿润的气候,同时从赤道区域向南,气候逐渐变得干旱;Hurowitz et al. (2017)对“好奇号”行驶路径上泥岩的矿物成分分析发现,Gale 撞击坑所在区域在早西方世呈现逐渐变暖的气候特征,指示了在西方纪火星全球变冷的气候背景下局部地区的气候变化存在特殊性。

火星水成地貌对于天体生物学研究也具有重要意义。火星古湖泊特别是开放系统古湖泊可能具有较长时间的水活动,是最可能存在宜居环境、保存生命痕迹的区域(Fassett et al. , 2008; Goudge et al. , 2012),因而也是火星原位探测的重点对象,“勇气号(Spirit)”、“好奇号”、“毅力号(Perseverance)”等火星车都选择了古湖泊盆地开展探测。目前,“好奇号”在 Gale 撞击坑内发现了大量水活动的证据,且存在较为稳定的具有中性 pH、低盐度的水环境(Grotzinger et al. , 2014, 2015; Hurowitz et al. , 2017),并且探测到了 C、H、O、S、N、P 等与生命相关的重要化学元素(Grotzinger et al. , 2014),支持了宜居环境的存在;同时在古老泥岩(~3.5 Ga)样品中检测到了热解产生的噻吩类、芳香族和脂肪族化合物,有机碳含量>50 nmol(Webster et al. , 2015; Eigenbrode et al. , 2018),尽管无法确定这些有机物是否为生物成因,但对于了解火星古湖泊中有机碳的保存及碳循环提供了有利信息。火星表面的干盐滩沉积有氯盐、硫酸盐等盐类矿物,如果火星曾经存在过生命,这些长期保存在极端干旱条件下的蒸发盐将为可能的生物标志物提供理想的保存环境,是开展天体生物学研究的重

要对象(Stivaletta et al., 2009; Huang Ting et al., 2018; Ye Binlong et al., 2019; Dang Yanan et al., 2020)。此外,对峡谷网、三角洲、外流河道等地貌的形成和持续时间的研究可为火星液态水活动提供时间约束,有助于确定宜居环境的存续时间(Hoke et al., 2011; Kereszturi, 2012)。

5 火星水成地貌研究亟待解决的问题

5.1 水成地貌的水源类型

火星上峡谷网、古湖泊等水成地貌的水源类型对于了解火星的古气候条件具有至关重要的作用。前人的研究已经提出了与大气降水、地下水、冰川融水等相关的多种水源供给模型(Baker et al., 1991; Baker, 2001; Clifford et al., 2001; Phillips et al., 2001; Mischna et al., 2003; Russell et al., 2003; Hanna et al., 2005; Fassett et al., 2008)。其中, Fassett et al. (2008)的研究表明,火星早期古湖泊的水源供给类型可能随古湖泊所处的海拔高度而变化,位置较高的古湖泊可能由大气降水形成的地面径流供给,而高程较低的古湖泊可能主要由地下水供给。不同的水源供给类型也形成了不同的峡谷形貌和水系特征。具有树枝状水系的古湖泊一般由地面径流供给,而具有较短的单一峡谷的古湖泊可能是由地下水在短时间内突然释放形成(Fassett et al., 2008; Goudge et al., 2015, 2016)。尽管如此,目前对火星峡谷网的形貌及其与水源类型的关系仍然缺少系统的研究,对于不同区域、不同时代的古湖泊的水源供给特征还有待查明,需要利用高分辨率遥感影像对峡谷网和古湖泊进行识别与水源追踪,并结合地质背景具体分析不同地质过程对峡谷网和古湖泊水源供给的贡献,获得对水成地貌水源的正确认识。

5.2 水成地貌所指示的火星水环境特征

火星水环境特征及其随时间的变化对于探索火星的环境宜居性及保存生命痕迹的可能性至关重要。开展水环境特征的研究需要对水成地貌中沉积物的矿物成分进行分析。近年来,美国实施的多项原位探测任务获得了大量关于火星局部区域的矿物成分和水环境的探测结果(Squyres et al., 2004; Wang et al., 2006; Grotzinger et al., 2014; Ruff et al., 2014; Hurowitz et al., 2017)。但是,由于巡视探测着陆点有限,对大区域范围内的成分研究主要依靠遥感光谱探测。目前,“火星快车(Mars Express)”探测器搭载的“可见光及红外矿物制图光谱仪(OMEGA)”获取了火星表面较高覆盖率的光

谱数据,但其空间分辨率相对较低,最高仅约为每像素 350 m;MRO 搭载的“火星专用小型侦察影像频谱仪(CRISM)”能够获得高达每像素 18 m 的可见光-近红外光谱数据,但高分辨率数据的空间覆盖率有限,在其运行的前 6 年仅覆盖火星表面约 2% 的面积(Carter et al., 2013)。因此,一方面有待于更多探测任务搭载高分辨率光谱仪,获得更多的遥感光谱数据,另一方面,也需要综合多种光谱数据,开发新的光谱分析方法,利用现有的光谱数据重点开展层状硅酸盐、氯盐、硫酸盐、碳酸盐等水成矿物的识别,综合分析矿物集合体的特征以及各类矿物在三角洲、湖泊盆地等水成地貌内的空间分布规律,更好地约束火星的水环境特征。

5.3 火星亚马逊纪水成地貌的成因

亚马逊纪是火星最年轻的地质时代,其具有最长的时间跨度,约为 31 亿年前至今。气候模拟及地质分析显示,亚马逊纪的火星气候寒冷干旱,水主要以冰的形式存在于火星两极和地下(Head et al., 2003; Madeleine et al., 2009; Carr et al., 2010)。但近年来的研究发现,亚马逊纪仍可能有地表水的活动并形成多种水成地貌(见第 3 节)。早期的观点认为,这些水流活动主要与突发性的地质事件如火山活动(Gulick, 2001; Fassett et al., 2006)和撞击事件(Morgan et al., 2009)导致的地下冰层融化相关。但随着高分辨率影像数据的获取,更多的地质证据表明亚马逊纪也可能存在相对较长时间地表液态水活动。Kite et al. (2017)对部分冲积扇的研究表明,在西方纪/亚马逊纪交界时期有至少 20 Ma 甚至超过 300 Ma 的时间内火星存在宜居环境,即能够使液态水在火星表面稳定存在。他们利用模型计算对火星古河道开展的研究也支持了亚马逊纪存在降雨导致的地表水活动(Kite et al., 2019)。Wilson et al. (2016)提出亚马逊纪古湖泊可能是在较长时间的湿冷气候条件下由冰雪融水供给而形成和存续。此外,当前火星表面依然持续形成的冲沟、复现性斜坡纹是否与水的活动相关也有待进一步研究。由此可见,有必要开展更广泛的亚马逊纪水成地貌的调查研究,探讨它们的形成机制和持续时间,这将为进一步了解亚马逊纪气候,探索当前火星的宜居性提供支持。

5.4 火星水成地貌与我国柴达木盆地地貌的类比

由于目前火星探测方法及探测数据有限,人类也难以在火星表面实地开展地质地貌的研究工作,故仅依靠现有的火星探测数据很难全面地回答水成

地貌的形成机制、演化过程、气候背景等问题,而开展比较行星学研究,对地球表面的类火星地貌进行实地调研则成为解决上述问题的重要途径。

近年来,柴达木盆地以其独特的地理和气候环境条件受到了国际行星科学界的广泛关注,成为了新的火星类比研究基地(Xiao Long et al., 2017; Xiao Long, 2021)。国内外多个研究组已经对柴达木盆地与火星的相似性开展了初步的对比研究(Mayer et al., 2009; Zheng Mianping et al., 2013; Kong et al., 2014; Anglés et al., 2017; Cheng Ziyi et al., 2017; Xiao Long et al., 2017; Xiao Long, 2021; Wang et al., 2018; Sun Yu et al., 2021)。在水成地貌的研究方面,已开展了与火星古湖泊内多边形地貌的类比研究(Dang et al., 2018, 2020; Cheng Ruilin et al., 2021),类火星倒转河道成因的研究(Zhao Jiannan et al., 2021)等。但是,目前的研究还较为初步,需要继续开展不同水源特征的河道形貌、古湖泊沉积物的水环境指示、三角洲和冲积扇沉积的形成演化及矿物特征等方面的类比研究,以更好地回答当前火星水成地貌研究中存在的问题。

6 结语

本文回顾了火星水成地貌的探测与研究历史,并着重分析了峡谷网、外流河道、古湖泊和水成扇状沉积等主要水成地貌类型的形貌、分布、年龄等地质特征,对它们所指示的古气候环境进行了探讨。尽管目前仍在诸多方面存在争议,但毋庸置疑的是,液态水曾经在火星表面广泛存在,并在火星地貌的塑造过程中起到了重要作用。在未来的研究中,仍需要在水成地貌的水源、火星水环境特征、亚马逊纪水成地貌以及与柴达木盆地相似地貌的类比分析等方面开展进一步的研究,更好地揭示火星表面的水活动历史。相信随着包括我国“天问一号”在内的多项探测任务的相继实施,会获得更为多样、更高分辨率的探测数据,为更深入地认识火星水成地貌,了解火星气候变化及宜居性提供支持。

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Advances in Martian water-related landforms

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Abstract

Liquid water plays an important role in shaping the surface of Mars, forming a variety of water-related landforms, such as valley networks, outflow channels, paleolakes, deltas and alluvial fans, which have always been the focus of Martian exploration and research. This paper summarizes the research progress on the exploration history, topographic and geomorphological features, and temporal and spatial distribution of Martian water-related landforms, and discusses the implication for Martian climate evolution and astrobiological research. On this basis, we propose that more study is still needed on the source of Martian water-related landforms, Martian aqueous environment, origin of Amazonian water-related landforms, and the comparative study between the water-related landforms on Mars and in the Qaidam basin, China, which will help us better understand the Martian water-related landforms as well as the Martian climate change and habitability.

Key words: Mars; water-related landforms; fluvial channel; lake; paleo-climate; habitability