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贵州清镇寒武系底部首次发现埃迪卡拉型盘状化石:生物学、埋藏学及其古地理意义

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内容提要:盘状化石是埃迪卡拉纪(Ediacaran, ≈震旦纪)最早被描述的生物分子,也是全球埃迪卡拉生物群最重要的组成部分,对于重建埃迪卡拉纪—寒武纪过渡时期的生态系统,了解"寒武纪大爆发"时期生物的早期演化至关重要。*Aspidella* 是埃迪卡拉纪圆盘状化石的一个形态属,也是全球分布的埃迪卡拉纪沉积物中的典型化石。本文描述了在贵州清镇埃迪卡拉系—寒武系桃子冲组下部硅质岩中,首次被记录的埃迪卡拉纪疑似 *Aspidella* 盘状化石(cf. *Aspidella*),表现为以同心圆环、中央凸起和凹痕为特征的圆盘,三维结构扫描观察到其明显的阶梯状圈层变化。我们倾向于认为桃子冲组 cf. *Aspidella* 作为底栖软躯体叶状生物的固着器,其内部沉积物是在海水正常沉积作用下形成的,并发现了含 Fe、Al 物质的固着器生物膜碎片。证实生物固着器官受到微生物席的影响优先保存,而茎干和复叶却消失不见,黏土和砂砾的差异压实作用导致死亡后的生物固着器的球壁上产生了阶梯状的轮廓。结合贵州清镇埃迪卡拉系—寒武系桃子冲组地层中出现的生物组合与华北、柴达木地块的埃迪卡拉纪生物地层的相似性,以及埃迪卡拉纪到寒武纪过渡时期的全球古地理格局,华南板块由中纬度持续地向华北、柴达木地块所处的低纬度区域漂移,环境的改变可能是导致埃迪卡拉纪晚期生物分子在华南寒武系地层中得到种群延续的诱导因素,并进一步扩展了经典埃迪卡拉型化石在时间和空间的分布。

关键词: cf. *Aspidella*;固着器官;埃迪卡拉生物分子;埋藏学;震旦纪;寒武纪

埃迪卡拉生物群的生态学研究与埃迪卡拉纪(Ediacaran, ≈震旦纪)—寒武纪过渡时期的生命演化辐射密切相关(Bambach et al., 2007; Srivastava, 2012),它拥有关于早期宏观进化和多细胞生物出现的重要信息(Srivastava, 2012)。盘状化石是埃迪卡拉生物群中最早被描述的生物分子(Billings, 1872),也是全球埃迪卡拉生物群最重要的组成部分(MacGabhann, 2007),这些化石通常会以铸模和凹痕的形态保存在硅质碎屑沉积物中(Gehling et al., 2000; Droser et al., 2006; Laflamme et al., 2013; Tarhan et al., 2015)。*Aspidella* 是埃迪卡拉纪圆盘状化石的一个形态属,具有丰富的形态特征,也是全球分布的埃迪卡拉纪沉积物中的典型化石(Gehling et al., 2000; Peterson et al., 2003; Droser et al., 2006; MacGabhann, 2007; Grazhdankin et al., 2008; Laflamme et al., 2010; Tarhan et al., 2010, 2015; Srivastava, 2012; Meyer et al., 2013; Menon et al., 2013; Narbonne et al., 2014; 唐烽等, 2014; Bykova et al., 2016; Moczydlowska et al., 2016; Pang Ke et al., 2021)。关于埃迪卡拉纪盘状化石的系统及生态位置一直是全球古生物学者研究争论的焦点,*Aspidella* 被认为是可能的刺胞动物,具有周期性掘穴和自主移动的能力(Menon et al., 2013),以及包含其作为软体动物、水母,甚至是气

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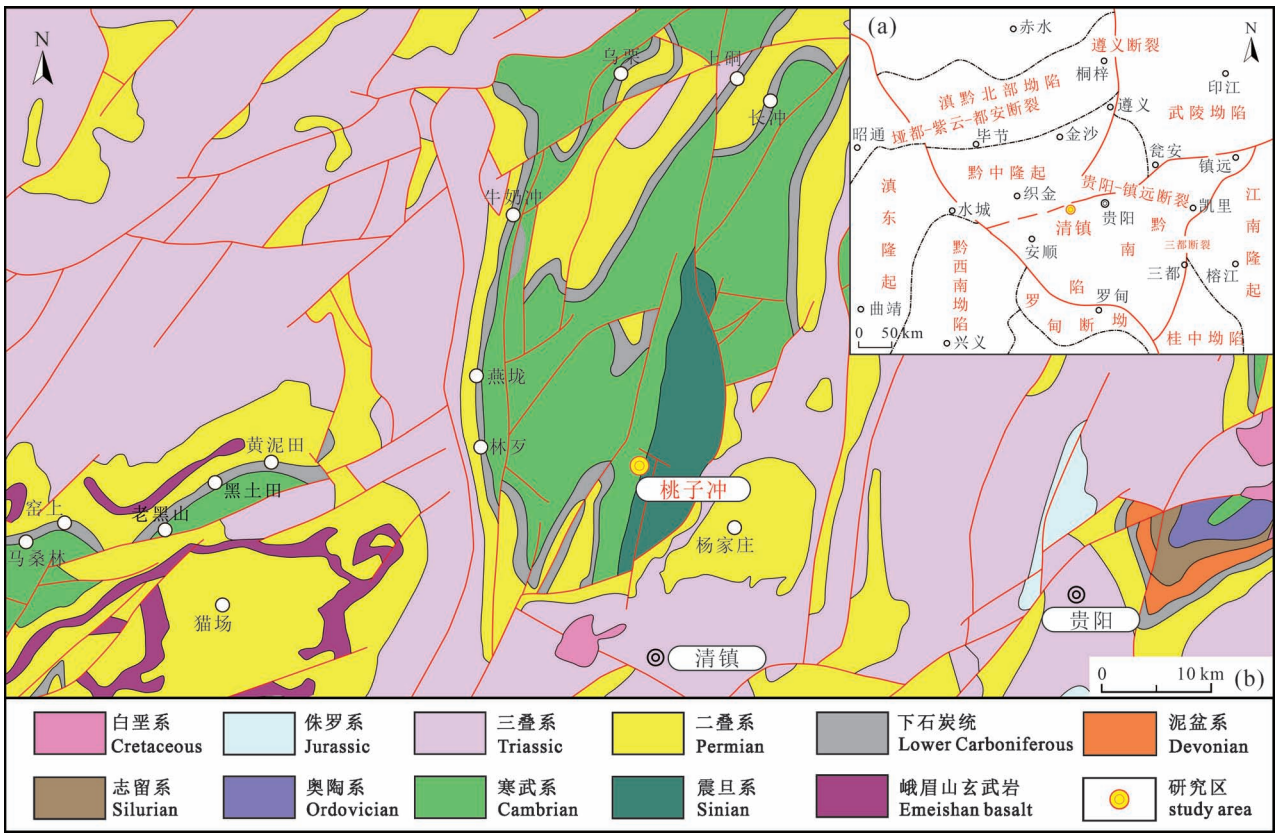

图 1 贵州清镇寒武系桃子冲组沉积剖面的位置及地质背景

Fig. 1 Location and geological background of the sedimentary profile of the Cambrian Taozichong Formation in Qingzhen, Guizhou

(a)黔中隆起及滇黔桂地区构造单元图(修改自牛新生等,2007);(b)贵州清镇桃子冲组区域地质图(修改自 Luo Chaokun et al., 2022)

(a) Tectonic unit map of the central Guizhou uplift region and the study area (modified from Niu Xinsheng et al., 2007); (b) regional geological map of Taozichong, Qingzhen, Guizhou Province (modified from Luo Chaokun et al., 2022)

体逃逸结构或微生物等非后生动物的观点(Gehling et al., 2000; Droser et al., 2006; MacGabhann, 2007; Grazhdankin, 2014; Liu et al., 2015)。而随着对全球部分地区所发现的与 *Aspidella* 相连的茎干、复叶进行深入研究,其圆盘状结构的印痕是埃迪卡拉纪底栖叶状软躯体生物的固着器官的观点被大多数学者所认可(Gehling et al., 2000; Peterson et al., 2003; Grazhdankin et al., 2008; Tarhan et al., 2010, 2015; Narbonne et al., 2014; Narbonne et al., 2014; 唐烽等, 2014; Moczydlowska et al., 2016; Pang Ke et al., 2021)。

我们在贵州清镇寒武系桃子冲组下部硅质岩中,发现了形态完好的盘状化石,是一种以同心环、中央凸起和凹痕为特征的圆盘,表现出明显的阶梯状圈层变化,具有 *Aspidella* 盘状化石的相似特征(Gehling et al., 2000; Tarhan et al., 2015),并将其归为 *Aspidella* 的相似属 cf. *Aspidella*,这是在华南寒武系地层中首次被记录的埃迪卡拉纪盘状化石,这一新的发现也扩展了经典埃迪卡拉型化石在时间和空间的分布。除此之外,我们还在桃子冲组下部的硅质磷块岩中发现了陕西迹 *Shaanxilithes* 化石,这也是典型的埃迪卡拉纪末期生物化石(华洪等, 2004; Zhou Chuanming et al., 2019; Pang Ke et al., 2021; Wang Xin et al., 2021)。同时,Mao Tie 等(2014)在清镇桃子冲组下部发现富含小壳动物化石的磷块岩具有明显的 $\delta^{13}C$ 负漂移现象,正指示着全球寒武纪生命大爆发的第一幕。说明清镇桃子冲组下部的 cf. *Aspidella* 等埃迪卡拉型生物化石,恰好记录了“寒武纪大爆发”这一次重要的全球事件。

化石形态不仅能反映出曾经存活的生物体内部结构,还能反映出这种生物结构可能被沉积、埋藏和成岩过程所改变的方式(MacGabhann, 2007; Tarhan

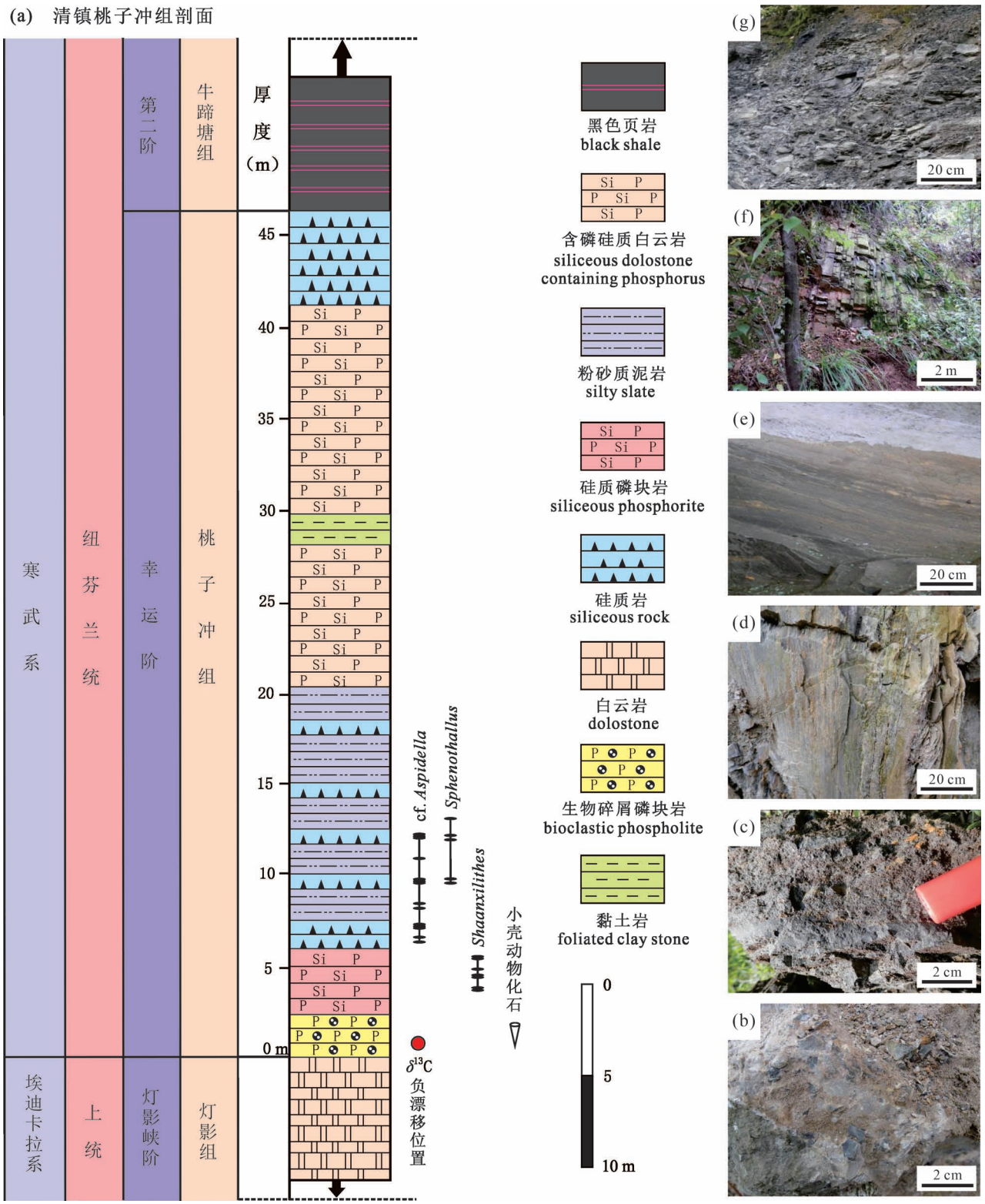

图 2 贵州清镇寒武系桃子冲组沉积剖面地层柱状图及岩性组合

Fig. 2 Stratigraphic column map and lithology association of the Cambrian Taozichong Formation in Qingzhen, Guizhou

(a)研究区地层柱状图,以及剖面上 cf. *Aspidella*、*Sphenothallus*、*Shaanxilithes* 和小壳动物化石的产出位置(小壳动物化石产出层位及 $\delta^{13}C$ 负漂移位置均来自 Mao Tie et al., 2014);(b)灯影组细粒白云岩;(c)桃子冲组生物碎屑磷块岩;(d)桃子冲组条带状泥质、硅质、磷质白云岩;(e)桃子冲组硅质白云岩水平层理、瘤状结构;(f)桃子冲组薄层硅质岩;(g)牛蹄塘组黑色页岩

(a) stratigraphic column map of the study area, and the location of cf. *Aspidella*, *Sphenothallus*, *Shaanxilithes* and small shell fossils on the section (both the production horizon of small shell fossils and the negative drift location of $\delta^{13}C$ are from Mao Tie et al., 2014). (b) fine-grained dolostone of the Dengying Formation; (c) bioclastic phosphorite of the Taozichong Formation; (d) banded argillaceous, siliceous, and phosphorous dolostone of the Taozichong Formation; (e) horizontal stratification and wart structure of siliceous dolostone of the Taozichong Formation; (f) thin-layered siliceous rock of the Taozichong Formation; (g) black shale of the Niutitang Formation

et al., 2010)。而对埃迪卡拉纪生物分子的古生物学和生态学的研究,正是重建埃迪卡拉纪—寒武纪过渡时期的生态系统,讨论生物多样性进化的重点(Gehling et al., 2000; Droser et al., 2006; Laflamme et al., 2010; Tarhan et al., 2010, 2015; Srivastava, 2012; Narbonne et al., 2014; Moczydlowska et al., 2016)。基于此,本文对贵州清镇寒武系桃子冲组 cf. *Aspidella* 盘状化石的保存形态、地球化学特征等方面进行了研究,旨在分析 cf. *Aspidella* 的生物学与生态学特征,以及其在寒武系地层中的保存机制,并重点解释了 cf. *Aspidella* 圆盘特殊的阶梯状圈层结构形成的埋藏过程。这对研究埃迪卡拉纪晚期生物分子在华南寒武系地层中得到种群延续的原因,丰富"寒武纪生命大爆发"的生物进化理论,重建埃迪卡拉纪—寒武纪过渡时期的生态系统,完善我们对埃迪卡拉纪—寒武纪过渡时期全球古地理背景的认识,提供了一个新的窗口。

1 地质背景

贵州清镇桃子冲组剖面(图 1)位于扬子地台"黔中隆起"南缘(Mao Tie et al., 2014;杨瑞东等,2017;Gao Lei et al., 2023),发育大型"古背斜"构造(牛新生等,2007;邓新等,2010;崔金栋,2013)。东吴运动后,"黔中隆起"与上扬子地台完全融合(牛新生等,2007;邓新等,2010;崔金栋,2013;Luo Chaokun et al., 2022)。早寒武世梅树村时期的古地理位置为浅海向洋延伸一侧含磷碳酸盐岩的淹没台地(Chen Jiyan et al., 2013;Mao Tie et al., 2014;毛铁等,2015;周克林等,2019;Xing Jieqi et al., 2021;Gao Lei et al., 2024)。该区为一套以白云岩、磷块岩和生物碎屑岩为主的海相地层(图 2)(邢裕盛等,1984;Chen Jiyan et al., 2013;Mao Tie et al., 2014;毛铁等,2015;杨瑞东等,2017;周克林等,2019)。研究区主要包括上埃迪卡拉统灯影组、过渡层寒武系桃子冲组(纽芬兰统幸运阶)和寒武系牛蹄塘组(纽芬兰统第二阶)地层(图 2a)(王砚耕等,1984;薛耀松等,2002;华洪等,2004;Mao Tie et al., 2014;毛铁等,2015;杨瑞东等,2017)。

研究区清镇采样剖面底部灯影组发育含燧石的细粒白云岩和水平层理(图 2b)。桃子冲组含磷岩系厚度大,近 50 m(图 2a),自下而上主要沉积角砾质生物碎屑磷块岩(图 2c)、粉砂质泥岩、硅质岩(图 2f)、硅质磷块岩、含磷硅质岩(图 2d),水平层状、瘤状构造发育(图 2e),属潮下低能环境(Mao Tie et al., 2014),水动力较弱,以潮下局限沉积环境为主,偶有强水动力潮坪沉积(Mao Tie et al., 2014)。剖面顶部的牛蹄塘组主要为一套致密块状的黑色页岩,水平层理发育(图 2g)。

2 材料与方法

本文所研究和拍摄的标本均采自贵州清镇寒武系桃子冲组剖面(图 2)。盘状化石和楔叶形虫 *Sphenothallus* 化石保存在桃子冲组中下部的黑色硅质岩中,陕西迹 *Shaanxilithes* 化石保存在桃子冲组下部的硅质磷块岩中(图 2a)。并使用 CorelDRAW 软件对图片进行排版设计,本文所讨论的化石材料均编号存放于贵州大学古生物研究中心。

小尺寸的标本使用 Leica-M250C 和 Leica-DVM6 显微镜系统拍摄,较大尺寸的标本使用尼康相机(D7000)拍摄。使用 Leica-DVM6 三维显微镜系统拍摄化石的三维视图图像。利用 HITACHI-SU8010 扫描电镜(Scanning Electron Microscope, SEM)和能谱仪(Energy Dispersive Spectrometer, EDS)对化石进行微观形态观察和微观化学分析。在 SEM—EDS 测试之前,在样品表面喷上一层薄金。化石样品的矿物组成采用全岩 X 射线粉晶衍射分析(X-Ray Diffraction, XRD),使用仪器为 PANalytical B. V. Empyrean 型 X 射线粉晶衍射仪,分析条件为:Cu Kα 靶,45 kV 工作电压,40 mA 工作电流,8°/min 扫描速度,2θ(°)范围为 6°~70°,利用 Jade 6.0 软件对主要矿物相进行识别和鉴定。显微成像、SEM—EDS 和 XRD 分析工作均在贵州大学进行。此外,部分化石样品的矿物学分析在中国科学院地球化学研究所矿床地球化学国家重点实验室进行,使用 LabRAM HR Evolution 和配备 20 倍物镜(NA 0.25)的开放空间显微镜进行拉曼光谱分析。

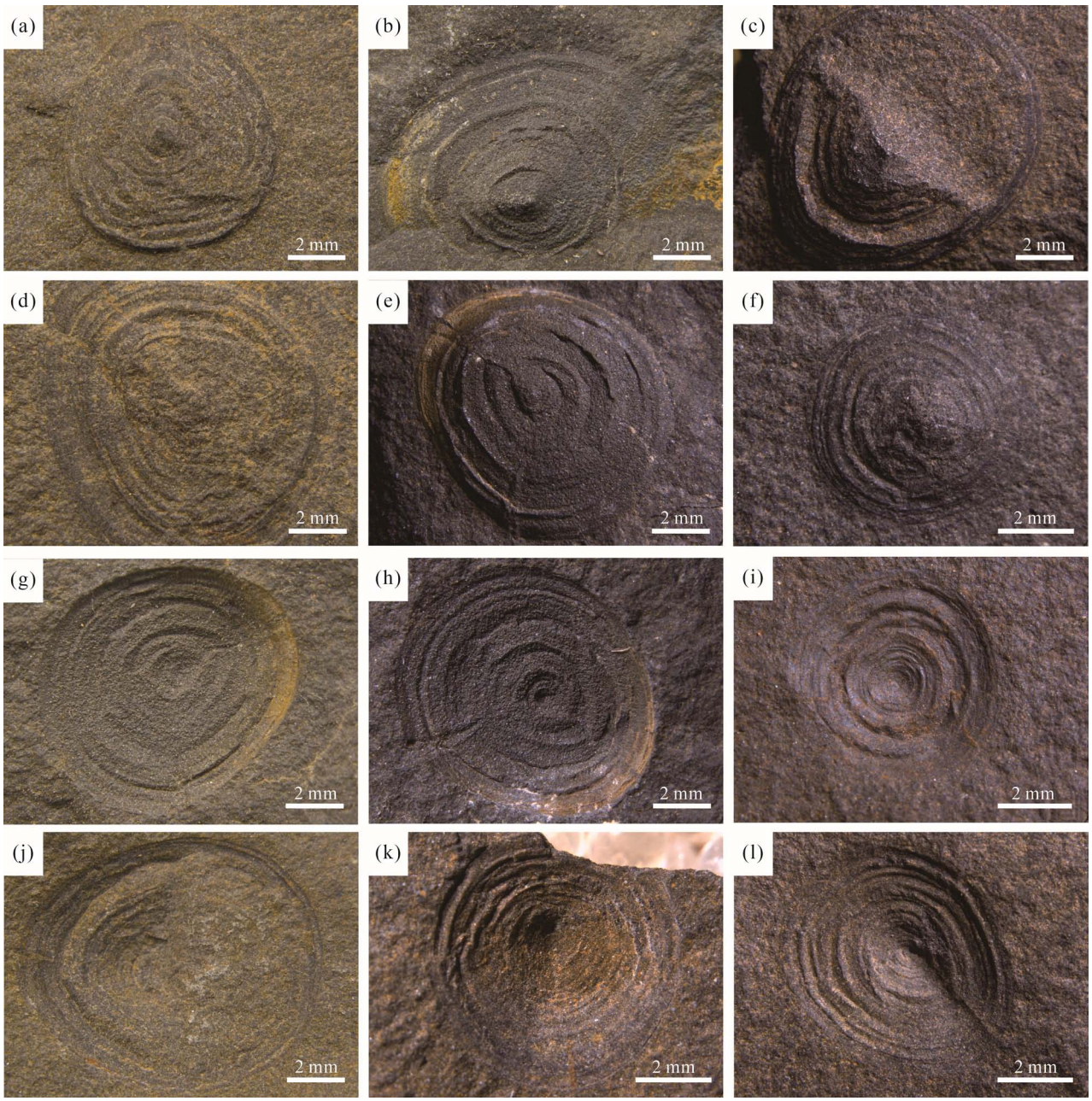

图 3 清镇寒武系桃子冲组硅质岩中 cf. *Aspidella* 盘状化石的保存形态

Fig. 3 The preserved forms of cf. *Aspidella* in the siliceous rocks of the Cambrian Taozichong Formation in Qingzhen, Guizhou

(a)—(f)cf. *Aspidella* 浮雕铸型以同心圆环和中心凸起为特征,化石编号:QA-R-02,QA-R-03,QA-R-10,QA-R-13,QA-R-15,QA-R-17;(g)—(l)cf. *Aspidella* 的凹陷形式以同心圆环褶皱和中心凹陷为特征,化石编号:QA-I-01,QA-I-03,QA-I-05,QA-I-08,QA-I-16,QA-I-19

(a)—(f) Relief castings of cf. *Aspidella* are characterized by concentric rings and central bulges, Nos.: QA-R-02, QA-R-03, QA-R-10, QA-R-13, QA-R-15, QA-R-17; (g—l) the mould of cf. *Aspidella* is characterized by concentric ring folds and central depressions, Nos.: QA-I-01, QA-I-03, QA-I-05, QA-I-08, QA-I-16, QA-I-19

光斑直径约为 2 μm,在 100~4000 cm^{-1} 范围内使用后向散射几何,使用 600l mm^{-1} 光栅,拉曼光谱由 532 nm 激光采集,功率约为 25 mW,连续两次采集,每次持续 20 s。

3　结果

3.1　cf. *Aspidella* 形态特征

埃迪卡拉纪 *Aspidella* 化石最初被认为是一种带有凸起的椭圆形圆盘,但并没有指定一个完整的模

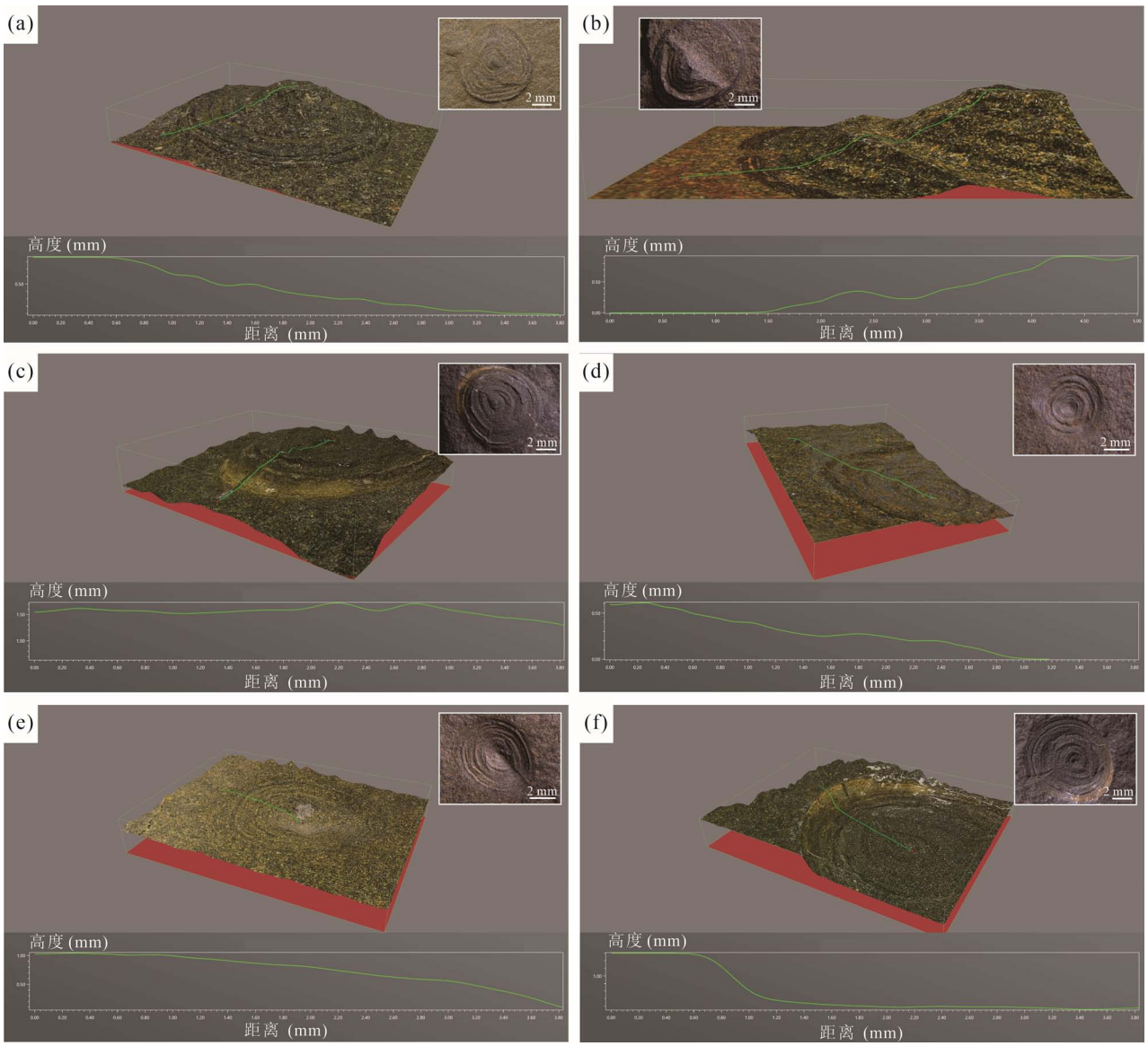

图 4 贵州清镇寒武系桃子冲组硅质岩中 cf. *Aspidella* 盘状化石的三维结构图

Fig. 4 The 3D morphological structure of cf. *Aspidella* preserved in the siliceous rock of the Cambrian Taozichong Formation in Qingzhen, Guizhou

(a)—(c)cf. *Aspidella* 浮雕铸型以同心圆环和中心凸起为特征,化石编号:QA-R-02,QA-R-10,QA-R-15;(d)—(f)cf. *Aspidella* 的凹陷形式以同心圆环褶皱和中心凹陷为特征,化石编号:QA-I-05,QA-I-19,QA-I-03

(a)—(c) Relief castings of cf. *Aspidella* are characterized by concentric rings and central bulges, Nos.: QA-R-02, QA-R-10, QA-R-15; (d)—(f) the mould of cf. *Aspidella* is characterized by concentric ring folds and central depressions, Nos.: QA-I-05, QA-I-19, QA-I-03

式标本(Billings, 1872),其形态凸度变化较大(Gehling et al., 2000; MacGabhann, 2007; Tarhan et al., 2015)。除了所有 *Aspidella* 共有的圆盘形状外,其特殊的形态特征还包括同心圆环、中央凸起、中央凹痕,从中心点向外辐射的脊、折痕和褶皱,或者存在茎干和复叶结构并以拖把形态所保存(Peterson et al., 2003; Grazhdankin et al., 2008; Tarhan et al., 2010, 2015; Narbonne et al., 2014; Pang Ke et al., 2021)。清镇 cf. *Aspidella* 化石出现在埃迪卡拉系—寒武系桃子冲组下部的黑色硅质岩中,保存为以同心环、中央凸起(图 3a—f)和凹痕(图 3g—l)为特征的圆盘。单个样本的直径通常在 5 mm 和 10 mm 之间(图 3),凸起和坳陷的高度在 0.6 mm 和 1.7 mm 之间(图 4)。这些浮雕铸型在最底层的边缘开始凸起,并向中间呈现同心环状阶梯式上升,形成最高点的中央凸台(图 3)。单个样本

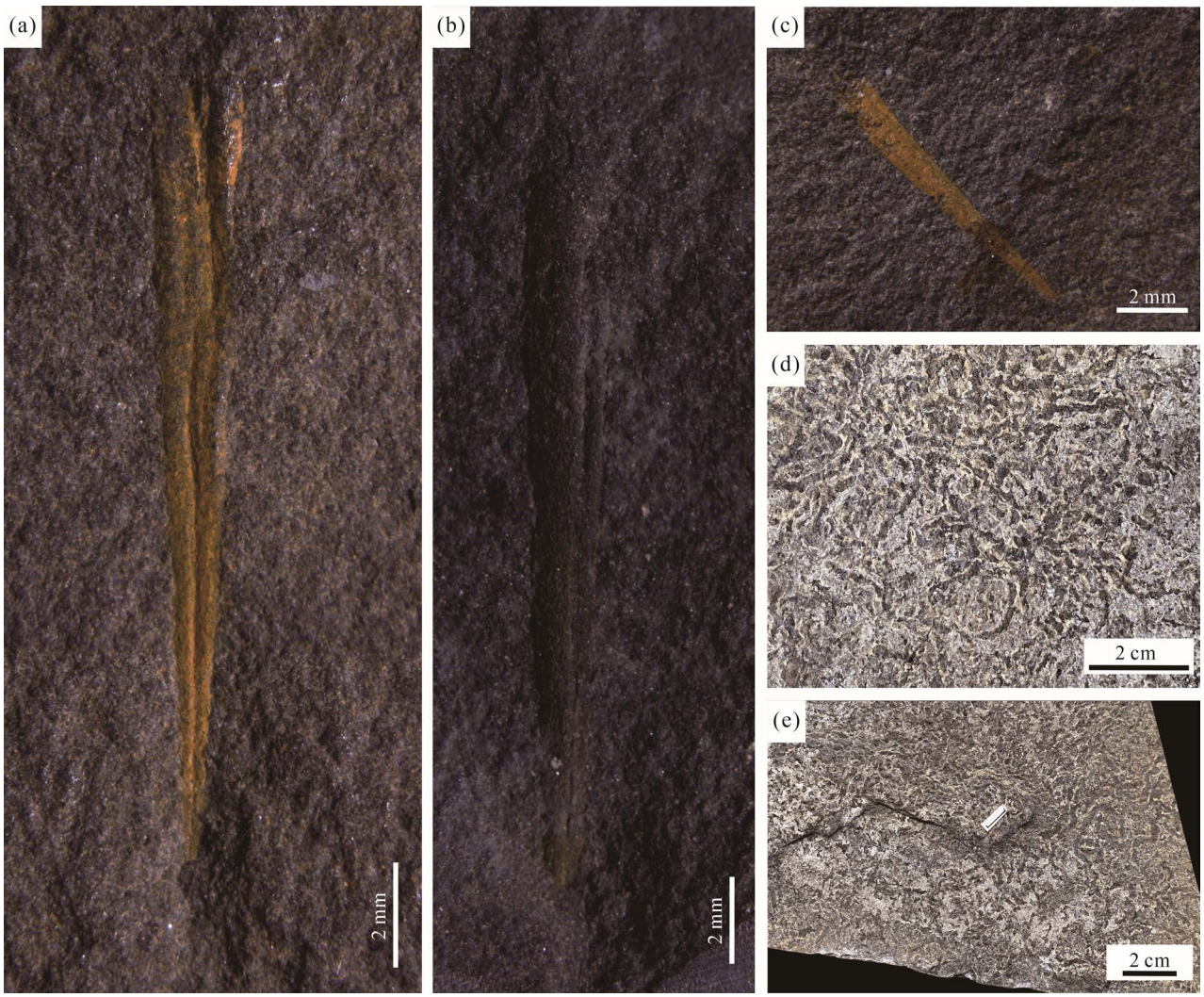

图 5 贵州清镇寒武系桃子冲组生物化石组合

Fig. 5 Fossils from the Cambrian Taozichong Formation in Qingzhen, Guizhou

(a)—(c)硅质岩中的楔叶形虫 *Sphenothallus*,蝶鞘细长,逐渐变细,个体相对直,孔口扩张率低,化石编号:QSP-R-01,QSP-R-04,QSP-R-05;(d)—(f)含磷硅质岩中的 *Shaanxilithes* 化石,个体间可相互叠覆,但无明显穿插现象,化石编号:QSH-I-01,QSH-I-02

(a)—(c) *Sphenothallus* fossils in siliceous rocks, QSP-R-01, QSP-R-04, QSP-R-05. The theca of *Sphenothallus* are slender, very gradually tapered, and individuals are relatively straight, with a low rate of apertural expansion; (d)—(e) *Shaanxilithes* fossils in phosphorous siliceous rocks, QSH-I-01, QSH-I-02. Individuals can overlap each other, but there is no obvious interpenetration phenomena

具有 5~10 个阶梯层,每层的高度变化在 0.05 mm 和 0.3 mm 之间(图 4)。

清镇 cf. *Aspidella* 盘状化石部分样本保存完好,劈开层面后可观察到同一圆盘标本的凸起铸型和凹痕印模(图 3)。常见内部铸型呈高度正(凸)的低浮雕到全浮雕保存粘附在上覆地层的底层面(图 3)。这些 cf. *Aspidella* 作为圆盘化石顶部外表面的浮雕铸型保存在底座上(图 3),通常被较细颗粒的沉积物快速掩埋,因而保存了高精度的形态细节,包括褶皱和阶梯状形态以及个体所特有的其他形态特征。但是并未保存有附着在圆盘化石上的生物茎干或复叶部分(图 3、图 4)。

3.2　生物组合特征

楔叶形虫 *Sphenothallus*(模式种:*Sphenothallus taijiangensis*)(Zhu Maoyan et al., 2000)归属于刺胞动物门,与盘状化石在贵州清镇桃子冲组硅质岩中同层出现(图 5a—c)。蝶鞘细长,逐渐变细,个体相对直,孔口扩张率低。长 8~18 mm,宽 1.0~1.8 mm,膨胀角为 2°~10°。管壁纵向增厚光滑,无横向条纹,基部附着盘不保留或缺失。本次发现的 *Sphenothallus* 化石与台江牛蹄塘组(Zhu Maoyan et al., 2000)所报道的化石在尺寸和形态上非常相

似。*Sphenothallus* 是古生代海相地层中的世界性分布化石,因为其有一个较短的锥形管,被认为是寒武纪早期固着在基底的掠食者(Chang Shan et al., 2018),同时,*Sphenothallus* 也是最早产生生物矿化骨骼的动物之一,能够在缺氧的环境下生存(Fatka et al., 2013)。

同时,桃子冲组下部的硅质磷块岩中发现的陕西迹 *Shaanxilithes* 化石表现为长带状(图 5d, e),不分枝,宽约 2~3 mm,表面具有许多密集排列的横向脊纹。一般同一条带状体的宽度基本保持稳定,密集顺层展布,纵横交叉,长短不一,弯曲程度不同,不具方向性。个体间可相互叠覆,但无明显穿插现象。前人通过对 *Shaanxilithes* 的深入研究,排除了其为遗迹化石或蠕形动物的可能,并与现生动物深海管状蠕虫进行形态学比较,将 *Shaanxilithes* 分类归为环节动物门多毛纲,是最早期的非矿化管壳生物,始端插于泥质或砂质基底中营固着生活(Wang Xin et al., 2021)。

3.3 地球化学特征

为探究清镇桃子冲组盘状化石的物质成分,我们对其进行了拉曼光谱点分析实验(图 6)以及 XRD 矿物成分分析(图 7)。cf. *Aspidella* 盘状化石的原位拉曼光谱显示,化石的凸浮雕(图 6a—a_2)、凹陷体(图 6b—b_2)和围岩(图 6c—c_2)具有一致的峰值特征,均表现出 SiO_2 的有效特征峰值(400~500 cm^{-1})(图 6a_2—c_2)。同时,在 1350 cm^{-1} 和 1600 cm^{-1} 附近有两个主要的宽带,分别称之为 D 峰(D-band)和 G 峰(G-band)(图 6a_2—c_2),是典型的无定形碳物质(disordered carbonaceous material, DCM)信号(苗雨霏等,2021),表明黑色物质富含干酪根(一种遭受了热变质作用后的有机碳物质)。同时,桃子冲组盘状化石粉末样品的 XRD 谱图同样表明,其矿物成分组成单一,只表现出 SiO_2 的特征峰(图 7)。说明清镇 cf. *Aspidella* 在沉积保存的过程中,留下了完整的圆盘状形态及内部一系列环状构造的印痕,而其生物实体的物质保存还有待进一步探究。

为了进一步探究桃子冲组 cf. *Aspidella* 化石在沉积过程中是否有生物膜碎片的保留,以及同期沉积的楔叶形虫 *Sphenothallus* 实体化石的元素组成特征,我们对其进行了 SEM—EDS 分析(图 8)。结果显示,虽然 cf. *Aspidella* 盘状化石具有浮雕和凹陷两种形态,但其主要元素的赋存状态是一致的。SEM—EDS 分析结果与拉曼光谱、XRD 矿物学分析结果相同,cf. *Aspidella* 保存在硅质岩中,O 和 Si 的含量分别约为 47.37~64.78 %和 19.19~49.66 %(图 8a、b)。并发现了少量的 Al 元素的赋存,含量为 2.17~11.33 %,说明其在成岩过程中,还有黏土矿物的加入(图 8a, b)。而我们发现,虽然楔叶形虫 *Sphenothallus* 化石与 cf. *Aspidella* 的围岩性质相同,但其壳体的物质组成复杂,主要由 C、O、Al、Si、Fe、K 元素组成,表现出壳体在沉积保存的过程中,受到黏土矿物的影响较大,并存在含 Fe、K 的生物膜(图 8c)。我们在 cf. *Aspidella* 的背散射电子显微照片下,同样发现了含 Fe 的物质碎片(图 8a),尤其是对清镇桃子冲组硅质岩中 cf. *Aspidella* 化石进行电镜能谱(SEM—EDS)面扫描,可以发现 cf. *Aspidella* 的浮雕铸型全部由含 Al、K 的生物膜覆盖(图 9a),而其凹痕状态下只在阶梯轮廓中出现 Al、K 的元素含量变化(图 9b)。结合同期沉积的楔叶形虫 *Sphenothallus* 生物膜特征(图 9c),我们推测其为桃子冲组 cf. *Aspidella* 盘状化石保存的固着器生物膜碎片。

根据 SEM—EDS 分析,并结合原位拉曼光谱以及 XRD 分析,判断清镇桃子冲组盘状化石 cf. *Aspidella* 是软躯体生物在海底的固着器形态化石,并非气体逃逸结构等地质沉积现象,其特殊的圈层结构是固着器在埋藏变异的过程中受到砂砾和黏土矿物的快速充填后所形成的。

4 讨论

4.1 生物学与形态学

全球分布的 *Aspidella* 类盘状化石除了存在共有的圆盘结构外,还会出现典型的扫把状的茎干和复叶的保存(Peterson et al., 2003; Grazhdankin et al., 2008; Tarhan et al., 2010, 2015; Narbonne et al., 2014; Pang Ke et al., 2021),其会受水流影响,从基底中拖拽生物固着器,使软体动物固着器形成褶皱状的圆盘(Peterson et al., 2003; Tarhan et al., 2010, 2015; Narbonne et al., 2014)。此外,贵州埃迪卡拉纪翁会生物群中发现的大量宏体藻类有丝状假根的固着器常与生物叶状体一同良好地保存在同一层面,并认为它们是从泥质海底中被水流作用拖拽出来的(Wang Ye et al., 2017, 2018)。我们首次在华南寒武系桃子冲组的地层中发现的 cf. *Aspidella* 圆盘状化石,并没有保存茎干和复叶的形态,仅保存着同心圆盘状的生物固着器(图 3),内部物质与基底围岩均为 SiO_2(图 6),没有任何直接证

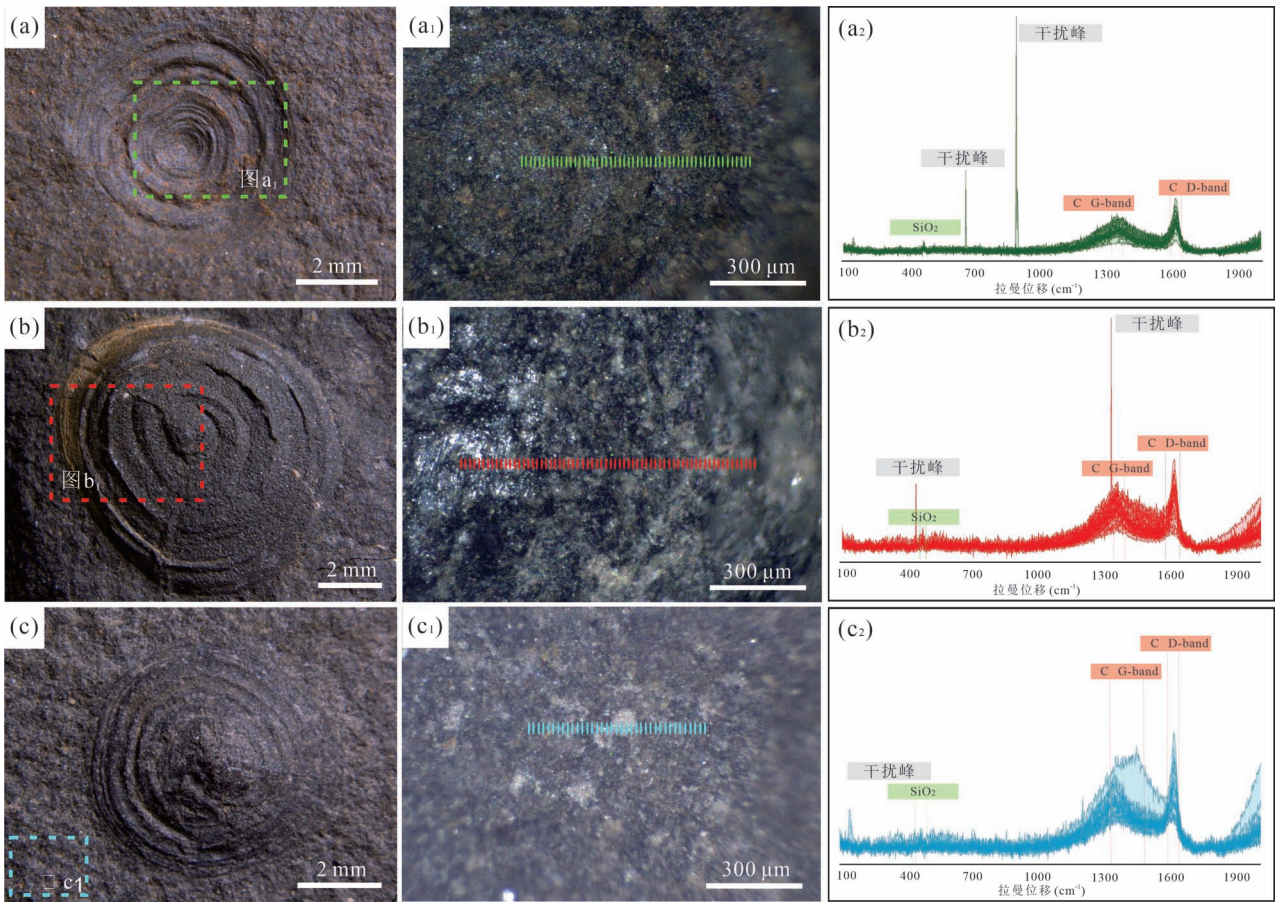

图 6 贵州清镇寒武系桃子冲组硅质岩中 cf. *Aspidella* 盘状化石的原位拉曼光谱分析

Fig. 6 In situ Raman spectroscopic analysis of cf. *Aspidella* preserved in the siliceous rock of the Cambrian Taozichong Formation in Qingzhen, Guizhou

(a)—(c)原位拉曼光谱分析区,化石编号:QA-I-05,QA-R-15,QA-R-17;(a_1)—(c_1)原位拉曼光谱分析点;(a_2)—(c_2)拉曼显微光谱点分析显示 SiO_2(400~500 cm^{-1})和 DCM(D 波段、G 波段)的特征峰

(a)—(c) In situ Raman spectrum analysis region, Nos.: QA-I-05, QA-R-15, QA-R-17; (a_1)—(c_1) in situ Raman spectrum analysis points; (a_2)—(c_2) Raman microspectroscopic point analysis showing the characteristic peaks of SiO_2(400~500 cm^{-1}), and bands (D-band, G-band) characteristic of DCM

明其生物起源的有机物保存,因而,其可能是非生物沉积。然而,关于非生物结构以及生物壳质化石的猜测不符合前文对桃子冲组 cf. *Aspidella* 的形态学及地球化学的分析,却与它们是埃迪卡拉纪软躯体生物形态遗迹的解释是一致的(MacGabhann, 2007; Moczydlowska et al., 2016)。清镇桃子冲组发现的 cf. *Aspidella* 仅保留同心圆环和中央凸起的圆盘状结构特点,也与澳大利亚南部的尼尔皮纳(Tarhan et al., 2015)和纽芬兰岛的费里兰(Gehling et al., 2000)等地分布的 *Aspidella* 圆盘化石保存状态相似。

清镇桃子冲组发现的圆盘化石直径在 5~10 mm 之间,集中在 8 mm 附近,尺寸跨度范围小,这与全球埃迪卡拉纪化石库中所记录的 *Aspidella* 尺寸大小一致,例如纽芬兰岛的费里兰(Gehling et al., 2000)、澳大利亚南部的尼尔皮纳(Tarhan et al., 2015)、俄罗斯的白海(Droser et al., 2006)等。此外,贵州翁会生物群中发现的 *Kullingia rotadiscopsis* sp. nov. 和 *Eoaequorea xingi* gen. and sp. nov. 同样具有清晰的碳质同心环纹和辐射状纹饰,但其多保存为压缩印痕,无明显的凸起高度变化,认为其可能是最早的浮游型水螅水母(Tang Feng et al., 2016)。而埃迪卡拉纪圆盘状化石的大小与形态变异密切相关(Gehling et al., 2000; MacGabhann, 2007; Tarhan et al., 2015),通常情况下,以放射形态为特征的个体直径>30 mm,拖把形态的个体直径>50 mm,而其他形态的圆盘个体的直径一般小至

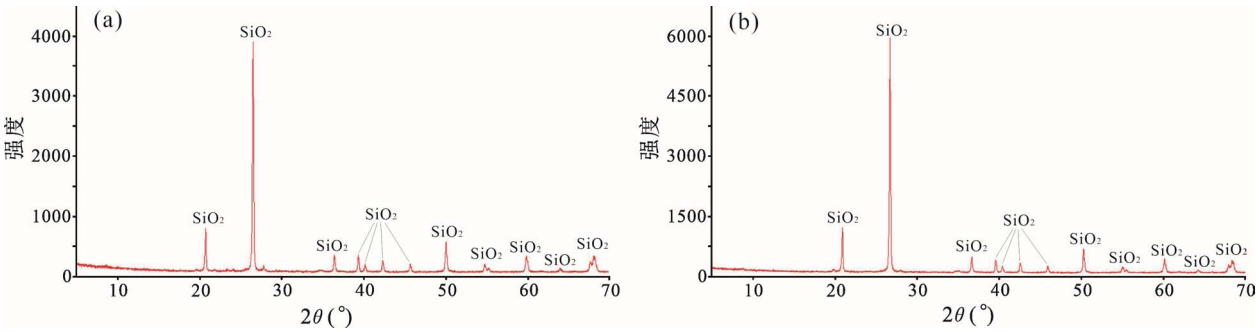

图 7 贵州清镇寒武系桃子冲组硅质岩中 cf. *Aspidella* 盘状化石 X 射线粉晶衍射图谱:粉末样品(QA-R-12, QA-R-16)的 XRD 谱图表明,样品的矿物组成单一,只有 SiO_2 的峰

Fig. 7 Powder-XRD patternsof cf. *Aspidella* preserved in the siliceous rock of the Cambrian Taozichong Formation in Qingzhen, Guizhou: the XRD patterns of the powder samples (QA-R-12, QA-R-16) show a single mineral composition, and only with the peaks of SiO_2

10 mm (Tarhan et al., 2015)。保存在同一地层上的 *Aspidella* 的尺寸稳定,不会有尺寸大小线性变化的情况出现,这主要归因于其个体抵抗单向水流扰动的不同能力,由其生物固着器大小所决定的(Tarhan et al., 2015; Moczydlowska et al., 2016)。同时,清镇桃子冲组发现的 cf. *Aspidella* 圆盘状化石种群,呈现出个体独立分布、没有叠生和互相干扰的特点(图 3)。而 *Aspidella* 的保存形态并不代表独立的个体发育阶段,只是由于海洋底栖软躯体生物死亡后受到沉积学、化学和生物地层条件的变化导致的个体固着器、茎干和复叶等生物特征沿着不同的埋藏路径保存(Gehling et al., 2000; MacGabhann, 2007; Tarhan et al., 2010, 2015)。而全球保存的埃迪卡拉纪褶皱形态圆盘和拖把形态的样本都存在明显的内部受力变形(Peterson et al., 2003; Grazhdankin et al., 2008; Tarhan et al., 2010, 2015; Narbonne et al., 2014; Pang Ke et al., 2021)。较大或较小尺寸的生物固着器个体都不太可能被风暴相关的水流连根拔起,因为较大的生物固着器个体其发育的茎干和复叶受力面积大,会出现水流拖曳现象,而后被切断,从而使保存的圆盘出现褶皱形态(Tarhan et al., 2010)。而较小的生物固着器个体发育短而细的茎干,受到较强的边界流体扰动,会被瞬间切断,因此会比中型个体更不可能形成拖把结构(Narbonne et al., 2014; Tarhan et al., 2015)。清镇桃子冲组 cf. *Aspidella* 圆盘呈现整齐规律的垂向生长状态,没有侧向的偏斜褶皱产生,生物固着器的内部形态也没有受到外力所产生的应变,我们猜测其是受到流速较快的单向边界流体影响,发育复叶的茎干与固着器的结合处被瞬间切断,没有出现水流拖曳茎干与复叶的现象,从而保留下完整的软躯体生物固着器形态。

全球发现的埃迪卡拉型化石通常保存在含氧沉积物中,例如在纽芬兰岛(Canfield et al., 2007),东欧地台(Johnston et al., 2012),以及华南陡山沱组(Xiao Shuhai et al., 2002; Li Chao et al., 2015)的地层中。而在埃迪卡拉纪生物演替中,海水的缺氧条件会被短暂的(生态时间尺度)氧化条件频繁中断,为需要氧气生存的生物提供有利的发育条件(Yuan Xunlai et al., 2011)。而埃迪卡拉纪 *Aspidella* 类软躯体生物种群代表了机会生物,生存在非缺氧的环境中,它们会利用间歇性的氧气条件迅速繁殖发育,从而导致了非常密集的底栖固着生物种群的出现(Gehling et al., 2000; Bykova et al., 2017)。清镇桃子冲组下部发育大量的小壳生物化石(Mao Tie et al., 2014),地化数据也表明此时的沉积水体处于富氧的环境下,海水营养物质和氧气相对充足(Gao Lei et al., 2024)。而桃子冲组下部沉积海水富氧的状态,也与 *Aspidella* 生物利用氧气条件机会性繁殖发育的特点相吻合,我们认为,清镇桃子冲组下部富氧、富营养的环境条件,也是其能够出现埃迪卡拉型后生生物的原因之一。

然而,在全球发现的埃迪卡拉型盘状化石,无论其保存方式和埋藏条件如何,化石体本身都缺乏有机物的存在,这也是后生动物细胞的典型特征,它们没有细胞壁但有细胞膜(Moczydlowska et al., 2016)。例如,华北辽南埃迪卡拉系兴民组发现的 *Aspidella* 印痕化石同样缺少有机质保存,表明其体

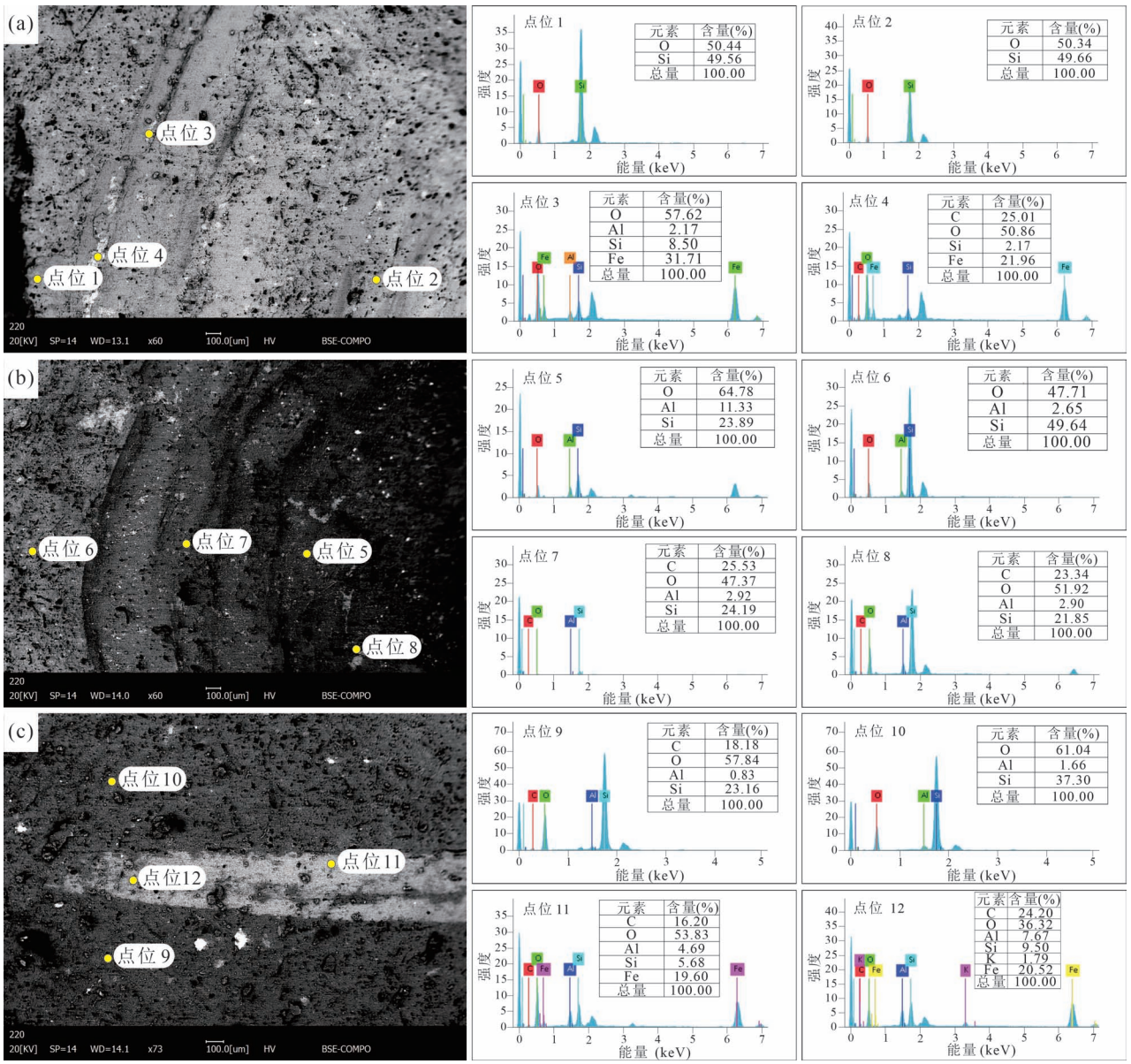

图 8 贵州清镇寒武系桃子冲组硅质岩中化石的 SEM—EDS 点分析

Fig. 8 SEM—EDS point analysis of fossils in the siliceous rocks of the Cambrian Taozichong Formation in Qingzhen, Guizhou

(a) cf. *Aspidella* 浮雕铸型的电镜图像和能谱分析结果显示,化石主要矿物成分为 SiO_2,部分区域充填黏土矿物,并发现含 Fe 的生物膜碎片,化石编号:QA-R-20;(b) *Aspidella* 凹痕形态的电镜图像和能谱分析结果表明,其主要成分为 SiO_2 和黏土矿物,化石编号:QA-I-15;(c) *Sphenothallus* 的电镜图像和能谱分析表明,化石体富含黏土矿物,存在含 Fe、Al 和 K 的生物膜,化石编号:QSP-R-08

(a) Electron microscope image and energy spectrum analysis results of relief castings of cf. *Aspidella*, No: QA-R-20. The main mineral component is SiO_2. Some areas are filled with clay minerals. Biofilm fragments containing Fe were found; (b) electron microscope image and energy spectrum analysis results of *Aspidella* indentations, No: QA-I-15. The main components were SiO_2 and clay minerals; (c) electron microscope images and energy spectrum analysis of *Sphenothallus* samples, No: QSP-R-08, the fossil bodies are rich in clay minerals, and there are biofilms containing Fe, Al and K

内的生物聚合物是不稳定的,并认为这与寒武纪早期后生动物产生的几丁质和胶原蛋白等难降解的生物聚合物形成鲜明对比(Moczydlowska et al., 2016)。因为缺少一个具有抗性的体壁来保护它们免受早期后生动物的生态扰动的影响,这可能也导致了早期埃迪卡拉后生生物群的灭绝(Laflamme et al., 2013)。

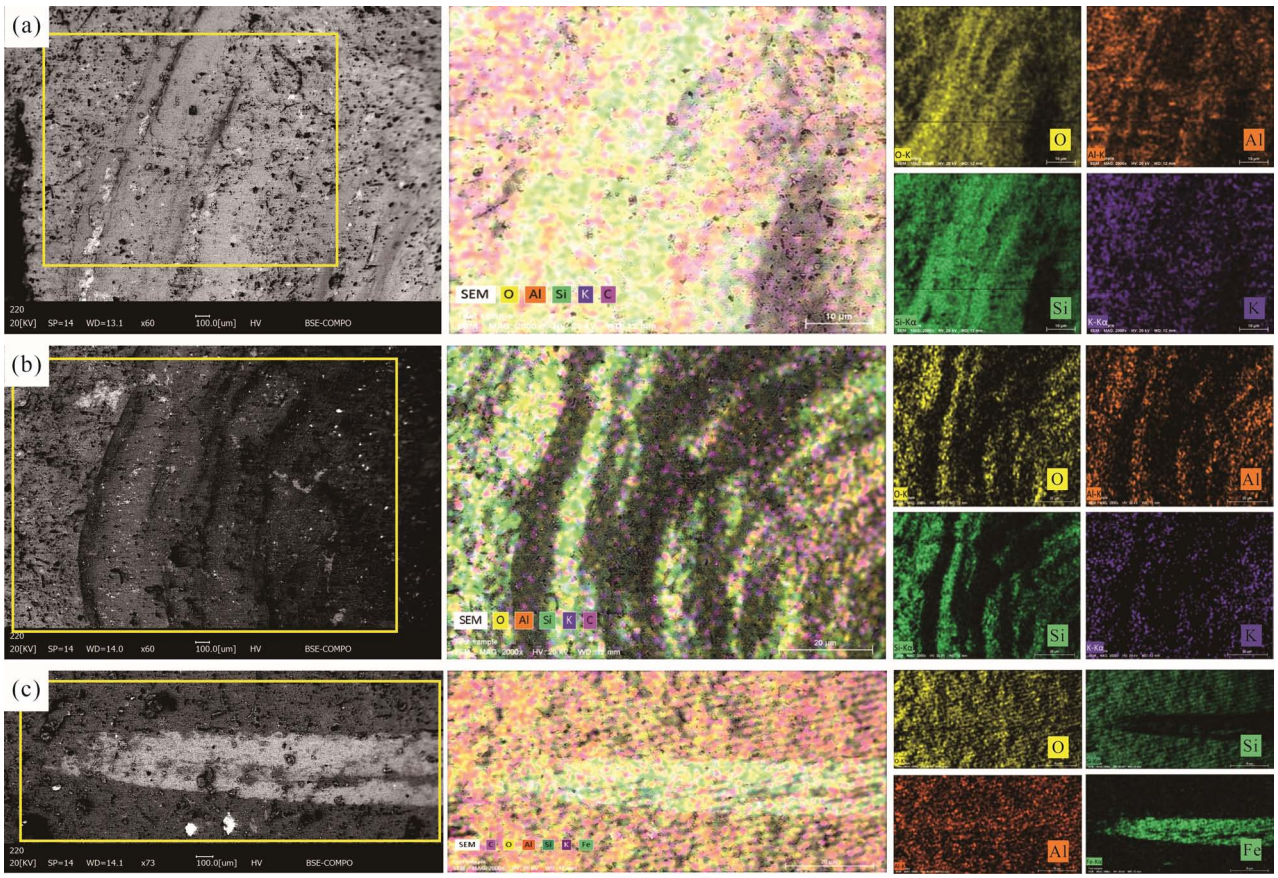

图 9 贵州清镇寒武系桃子冲组硅质岩中化石的 SEM—EDS 面扫描

Fig. 9 SEM—EDS surface scanning of fossils in the siliceous rocks of the Cambrian Taozichong Formation in Qingzhen, Guizhou

(a) cf. *Aspidella* 浮雕铸型的 SEM—EDS 面扫描分析结果,化石编号:QA-R-20;(b) cf. *Aspidella* 凹痕形态的 SEM—EDS 面扫描分析结果,化石编号:QA-I-15;(c) *Sphenothallus* 化石的 SEM—EDS 面扫描分析结果,化石编号:QSP-R-08

(a) Results of SEM—EDS surface scanning analysis of relief castings of cf. *Aspidella*'s, No: QA-R-20; (b) results of SEM—EDS surface scanning analysis of *Aspidella* indentation, No: QA-I-15; (c) results of SEM—EDS surface scanning analysis of *Sphenothallus*, No: QSP-R-08

4.2 保存机制与埋藏学

全球埃迪卡拉纪盘状化石保存的一个显著特征是其作为底栖软躯体生物的固着器结构,内部由富含二氧化硅的砂岩所充填(Gehling et al., 2000; Laflamme et al., 2010)。我们在清镇桃子冲组 cf. *Aspidella* 的背散射电子显微照片下(图 7),发现了含 Fe、Al 元素的物质碎片,而其固着器内外物质保存均为单一的 SiO_2。而从全球发现的 *Aspidella* 化石,都缺少碳质有机物的保存,这表明构成海洋底栖软躯体生物固着器的细胞膜有机物不具有抗性(Moczydlowska et al., 2016)。而 Laflamme 等(2010)对纽芬兰岛的费里兰埃迪卡拉地层中的 *Aspidella* 化学成分分析,表明生物膜在早期石化的生物固着器周围保留了由 Al—Mg—Fe 构成的三维微生物层。S、Fe、Ti 等元素是软躯体动物薄膜涂层最重要的组成部分(Toporski et al., 2002)。此外,大量研究也认为,微生物在寒武纪和更年轻地层的化石保存中,起到了分解腐烂生物膜并促进矿物沉淀的作用(Briggs et al., 2005; Gaines et al., 2008; Raff et al., 2008; Laflamme et al., 2010)。并强调生物膜会在微生物席的作用下释放 N、P、S、Mg、K、Ca、Na 和 Fe 等元素,与周围以硅为主的粗粒沉积物相比,其大部分独立存在于细粒物质中(Westall et al., 2006; Laflamme et al., 2010)。结合清镇桃子冲组 cf. *Aspidella* 的 SEM—EDS 分析结果,以及同期沉积的楔叶形虫 *Sphenothallus* 生物膜特征,我们认为这些 Fe、Al 物质应该是桃子冲组 cf. *Aspidella* 生物固着器的生物膜碎片。

而清镇桃子冲组 cf. *Aspidella* 表层含 Fe 生物膜碎片的存在,也为其固着器结构在沉积埋藏过程中存在微生物席作用提供了直接证据(Moczydlowska et al., 2016),而其间接证据也可以从微生物引起

的纹层状沉积结构中推断出来(Gehling, 1999; Gehling et al., 2009, 2013; Noffke, 2010; Noffke et al., 2013; Mariotti et al. 2014; Tarhan et al., 2015)。Moczydlowska 等(2016)发现,在埃迪卡拉纪软躯体生物固着器细粒包裹层与沉积物边界附近,存在黄铁矿层,认为在这些生物膜中存在硫酸盐还原细菌。死亡后的生物固着器结构为浅层沉积深度的厌氧微生物提供了丰富的高代谢有机物,促进了微生物硫酸盐的还原作用(Bykova et al., 2017)。细菌硫酸盐的还原作用可以导致黄铁矿等 Al—Mg—Fe—S 矿物的沉淀,加速软躯体动物残骸的化石化(Briggs, 2003)。而埃迪卡拉纪地层中丰富的微生物席也反映了异养掘食动物的缺乏,促进了软躯体生物的保存(Gehling, 1999; Callow et al., 2009)。随着微生物席上底栖软躯体动物茎干上复叶生长,微生物会聚集并包裹生长出复叶的生物固着器,埃迪卡拉纪圆形到球茎状的生物固着器缺乏生根结构,可能更依靠于微生物席所提供的坚固表面(Seilacher, 1989; Laflamme et al., 2008; Laflamme et al., 2010)。随着时间的推移,微生物菌落会生长并覆盖固着器的上表面,将它们粘在基底适当的位置(Laflamme et al., 2010)。与 *Aspidella* 相关的生物可能生活在微生物席内或垫下,其茎干和复叶突出在垫外并进入水体之中(Droser et al., 2006; Tarhan et al., 2010)。这一生长假设在纽芬兰岛、南澳大利亚、俄罗斯白海的 *Aspidella* 化石的保存中得到证实,并被称为“席垫”结构(Under-mat structures)(Droser et al., 2006)。这也导致清镇寒武纪桃子冲组底栖软躯体生物在相同的水动力条件下,其固着器受到微生物席的影响能够优先保存,没有发生腐烂,而茎和复叶却消失不见,最终形成 cf. *Aspidella* 盘状化石。

关于埃迪卡拉纪盘状化石的内部沉积物的来源及充填方式,学术界至今争论未休。有学者认为,埃迪卡拉纪底栖软躯体生物可以通过胃腔将沙粒吞噬并吸入体内,其固着器内部沉积物充填是在生长期间发生的(Seilacher, 1992; Seilacher et al., 2003),目的是为了增加生物固着器的结构刚性,提高生物代谢的表面积和体积比(Seilacher, 1992; Dzik, 1999, 2002; Seilacher et al., 2003; Laflamme et al., 2009, 2010)。而大部分学者认为,*Aspidella* 化石内部的沉积物是在生物固着器与茎干、复叶被水流切断之后,球茎被同期沉积的海水中砂砾、黏土等物质充填而后受到变形压实作用形成的(Gehling et al., 2000; MacGabhann, 2007; Tarhan et al., 2010, 2015)。而底栖软躯体生物的固着器垫子具有一定的弹性和结合力,能够以相对的刚性来抵抗海水扰动的影响(Tarhan et al., 2010)。Bykova 等(2017)对 *Aspidella* 化石的固着器、茎干、复叶和沉积物基质进行了 $\delta^{13}C$、$\delta^{18}O$、$\delta^{34}S$ 的地球化学分析,认为其生物固着器是通过压实沉积物胶结作用被矿化和保存的。而在贵州瓮会生物群的炭质化石中,宏体藻类沉积物之上的部分也易于变形、折断和相互折叠,导致难以区别固着器和叶状体,并认为其宏体藻类的固着器也历经了压膜变形和成岩变形(Tang Feng et al., 2016; Wang Ye et al., 2017, 2018)。清镇桃子冲组出现的 cf. *Aspidella* 盘状化石,无论是浮雕铸型还是凹痕形态,其与构成基底的砂砾岩性均保持一致,在物质成分上也没有明显的变化(图 6、图 7、图 8),因此,我们更倾向于认为清镇桃子冲组 cf. *Aspidella* 盘状化石内部沉积物是在海水正常沉积作用下形成的,并没有生命过程的参与。

软沉积物中球状物体的变形方式取决于其原始形状、结构材料以及埋藏过程中所涉及的特定成分、厚度和分层顺序(Gehling et al., 2000; Droser et al., 2006; Tarhan et al., 2010, 2015; Srivastava, 2012; Menon et al., 2013; Narbonne et al., 2014)。而埃迪卡拉时期底栖软躯体动物的固着器会在黏土和沙砾的差异压实作用产生阶梯状的轮廓,然后完全坍塌并被沙砾填充铸造(Gehling et al., 2000; Tarhan et al., 2010, 2015)。与沙砾相邻的剖面部分将被保存下来,而与黏土相邻的剖面将会变平和缩短(Gehling et al., 2000)。通过对清镇桃子冲组 cf. *Aspidella* 盘状化石的阶梯形态进行研究(图 4),我们认为其化石圈层的单层高度变化可以代表基底的砂砾厚度,单层的平面长度变化代表基底的黏土厚度,构成基底的沙砾和黏土的相对比例是控制清镇桃子冲组 cf. *Aspidella* 盘状化石形态保存的重要因素。

综上所述,我们认为清镇寒武系桃子冲组 cf. *Aspidella* 作为底栖软躯体生物的固着器部分,依靠微生物席的作用嵌入在砂砾与黏土构成的交替混合基底之中,其茎干和复叶突出在水体内并垂向生长(图 10a)。随着水流单向扰动作用增强,底栖软躯体生物的茎干和复叶在应力作用下发生形态应变(图 10b),水流的冲击作用导致茎干与固着器的结合处被切断(图 10c),底栖软躯体生物的固着器保留在基底之上,进入沉积埋藏阶段(图 10d),切断的

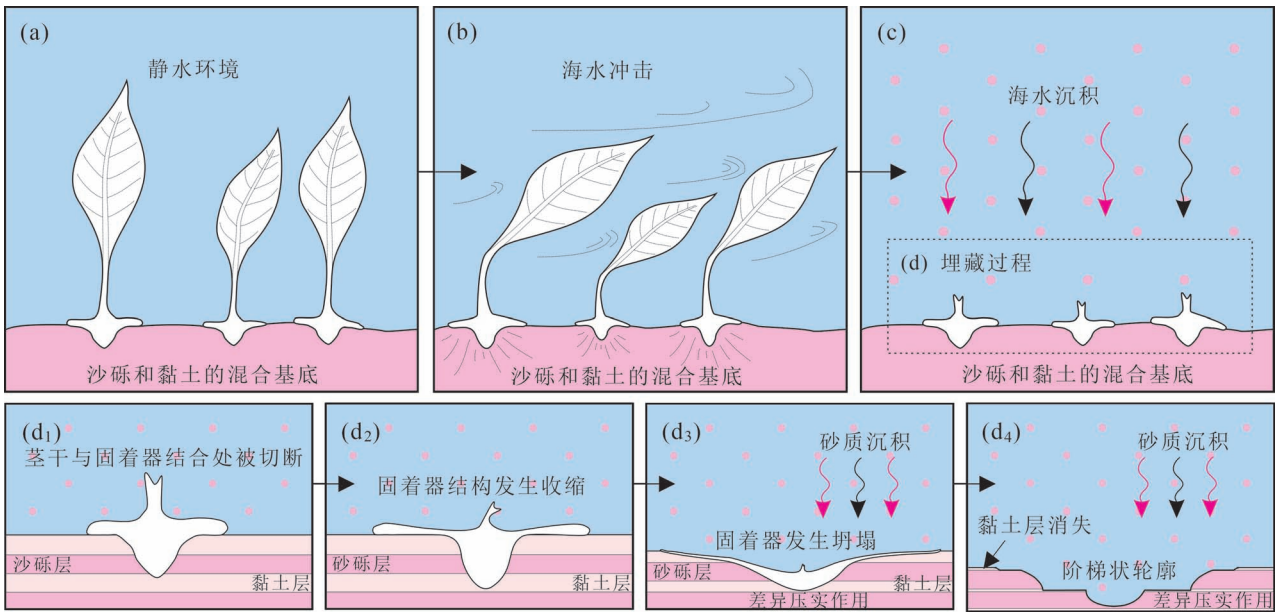

图 10 贵州清镇寒武系桃子冲组硅质岩中 cf. *Aspidella* 盘状化石的保存和埋藏过程

Fig. 10 Preservation and burial process of cf. *Aspidella* preserved in the siliceous rocks of the Cambrian Taozichong Formation in Qingzhen, Guizhou

(a)生物固着器附着在微生物结合的砂砾与黏土构成的交替基底之中,其茎干和复叶突出在水体内垂向生长;(b)水流单向扰动作用增强,使底栖软躯体生物的茎干和复叶在应力作用下发生形态应变;(c)水流的冲击作用导致茎干与固着器的结合处被切断;(d)生物固着器保留在基底之上,进入沉积埋藏阶段;(d_1)水流导致固着器与茎干、复叶的分离,茎干和复叶被水流作用带走消失;(d_2)固着器内部的生物体液流失,其结构发生收缩;(d_3)在被砂砾填充掩埋后,球茎坍塌并开始腐烂;(d_4)黏土和砂砾的差异压实作用致使固着器的球壁产生阶梯状的轮廓

(a) Holdfast structures were embedded in a mixed sediment base composed of sand and clay by the action of a microbial mat. The stems and compound leaves protruded vertically in the water column and grew vertically; (b) the effect of unidirectional flow disturbance was enhanced by increased current flow, and the stem and leaves of benthic soft-bodied organism experienced morphological strain under the action of hydrodynamic drag; (c) the impact of the water flow caused the stem and leaves to be severed at the junction with the holdfast; (d) the holdfast remained above the basement and entered the sedimentary burial stage; (d_1) water flow led to the separation of the holdfast from the stem and leaf, and the stem and leaf were carried away by the water flow and disappear; (d_2) the biological body fluid inside the holdfast was lost and its structure shrank; (d_3) after being suffocated by sand, the bulb collapsed and began to rot; (d_4) the differential compaction of clay and sand caused the holdfast ball wall to produce a stepped profile

茎干和复叶部分被水流作用带走消失(图 10d_1)。而切断茎干之后,固着器内部的生物体液可能会发生流失(Tarhan et al., 2010),固着器结构发生收缩(图 10d_2)。在被砂砾填充掩埋后,球茎坍塌并开始发生腐烂(图 10d_3)。由于生物固着器结构最初被嵌入在砂砾与黏土交替层的基底上,黏土和砂砾的差异压实作用会在固着器的球壁上产生阶梯状的轮廓(图 10d_4)。在这一过程中,海水中的砂质持续沉降,在这种有利于快速沉积和掩埋的条件下,固着器坍塌后的中空结构很快被砂砾填满(Gehling, 1999),所产生的砂质铸型也被保存为附着在覆盖层底部凸起的阶梯状 cf. *Aspidella* 圆盘结构(图 3)。

4.3 华南板块古地理意义

除了 *Aspidella* 等盘状化石外,陕西迹 *Shaanxilithes* 化石也是一个潜在的埃迪卡拉纪末期的指示化石,其化石沿限较短(Zhou Chuanming et al., 2019; 王欣, 2019; Pang Ke et al., 2021),目前,已在华北地块(Shen Bing et al., 2007; Meyer et al., 2012; Yang Jie et al., 2013)、柴达木地块(Shen Bing et al., 2007; Pang Ke et al., 2021)、印度(Tarhan et al., 2014)、西伯利亚(Grazhdankin et al., 2008)、纳米比亚(Darroch et al., 2016)等地的埃迪卡拉纪晚期地层中被发现。除本文外,华洪等(2004)也曾在华南地块清镇桃子冲组的地层中发现了 *Shaanxilithes* 化石,并认为它很可能与南澳大利亚的标本一样,是一类表附生长的钙化藻类。而 Wang Xin 等(2021)则认为 *Shaanxilithes* 归属于环节

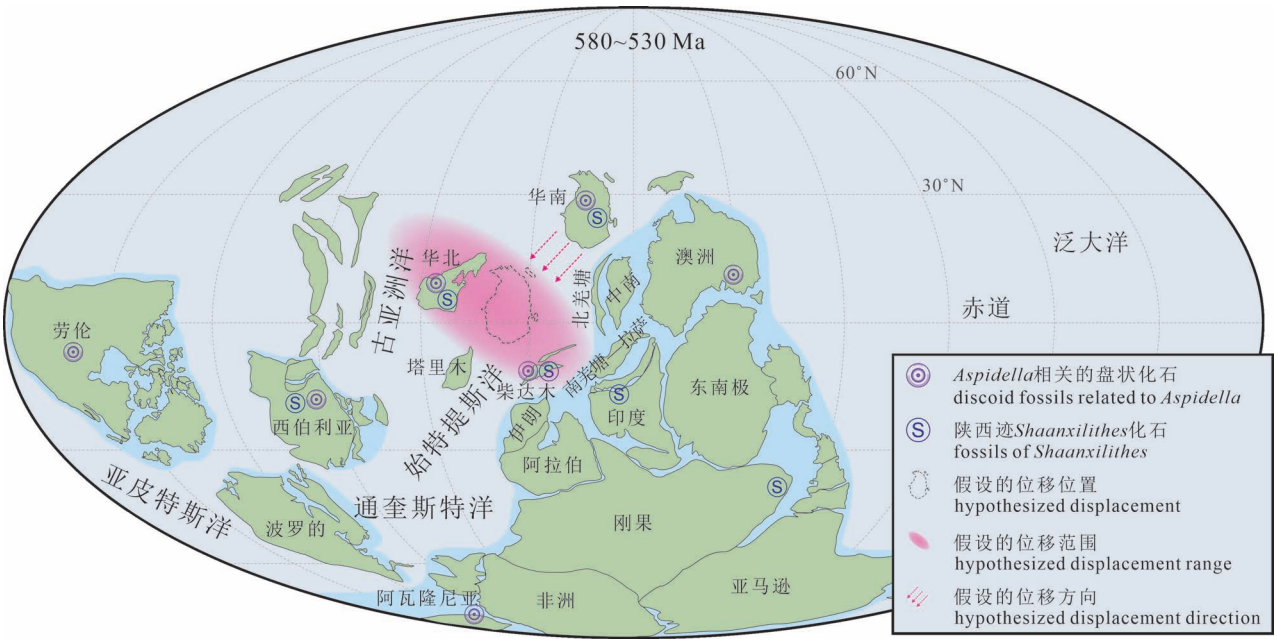

图 11 华南板块埃迪卡拉系—寒武系古地理位置建议(修正自 Zhao Guochun et al. , 2018, 2021),化石的分布在本文和 Pang Ke 等(2021)中进行了总结

Fig. 11 Proposed paleogeographic locations for South China Plate during Ediacaran—Cambrian period (modified from Zhao Guochun et al. , 2018, 2021), distributions of fossils are summarized herein and in Pang Ke et al. (2021)

动物门多毛纲,是最早期的非矿化管壳生物。同时,薛耀松等(2002)报道了在清镇桃子冲组下部硅质白云岩中出现的瓶状化石,认为它与华北埃迪卡拉系高家山生物群中的 *Protolagena limbata* 非常相似。而我国目前所报道的发现于下寒武统的瓶状化石,均与小壳动物化石紧密共生(钱逸等,2000)。然而,贵州清镇桃子冲组是埃迪卡拉系灯影组之上、寒武系牛蹄塘组之下的一套磷硅质组合(图 2),根据黔中地区灯影组上段普遍缺失的现象,桃子冲组与灯影组浅灰色微晶白云岩之间应该为假整合接触关系,其底界并无跨入埃迪卡拉系的证据(薛耀松等,2002)。华洪等(2004)同样认为,清镇桃子冲组出现的陕西迹 *Shaanxilithes* 化石、以及瓶状化石可以与高家山段进行对比,推测在清镇地区可能残存有部分灯影组上部的地层,而桃子冲组底部存在一个假整合面。为此,Mao Tie 等(2014)曾对清镇桃子冲组地层进行了 $\delta^{13}C$ 分析,发现在梅树村期底部富含小壳动物化石的生物碎屑磷块岩层位出现了全球性的 $\delta^{13}C$ 负漂移事件(图 2),因此将桃子冲组小壳动物首次出现的位置划为埃迪卡拉系与寒武系之间的界线,并认为此时正对应着全球寒武纪生命大爆发的第一幕。

此外,在我国柴达木板块北缘的欧龙布鲁克微陆块,也发现了 *Aspidella* 和 *Shaanxilithes* 共生的埃迪卡拉纪末期的全吉山生物组合,结合其冰川沉积物特征,认为在埃迪卡拉纪晚期,柴达木地块很可能位于华北地块附近,同时,处在东冈瓦纳和劳伦蒂亚之间的中高纬度地区(Pang Ke et al. , 2021)。然而,由于新元古代雪球地球期间,大陆冰川可以延伸到中低纬度,并对全球古地理重建产生误导(Hoffman, 1991, 1999; Hoffman et al. , 2009)。本文更倾向于古地磁手段所重建的 580~530 Ma 全球古地理格局,认为该阶段华南板块位于北半球中纬度区域,而华北板块与柴达木板块位于赤道附近的低纬度区域(图 11; Zhang Shihong et al. , 2015; Zhao Guochun et al. , 2018; Zhao Hanqing et al. , 2021)。这也与目前全球所发现的 *Aspidella* 等盘状化石和 *Shaanxilithes* 陕西迹化石共生组合的产出层位(Gehling et al. , 2000; Peterson et al. , 2003; Droser et al. , 2006; MacGabhann, 2007; Shen Bing et al. , 2007; Grazhdankin et al. , 2008; Laflamme et al. , 2010; Tarhan et al. , 2010, 2014, 2015; Meyer et al. , 2012, 2013; Srivastava, 2012; Yang Jie et al. , 2013; Menon et al. , 2013; Narbonne et al. ,

2014; Bykova et al., 2016; Darroch et al., 2016; Moczydlowska et al., 2016; Pang Ke et al., 2021), 在埃迪卡拉纪晚期处在全球中低纬度区域的观点相一致(图 11; Zhang Shihong et al., 2015; Zhao Guochun et al., 2018; Zhao Hanqing et al., 2021)。而埃迪卡拉纪到寒武纪过渡时期,华南板块由中纬度持续向华北、柴达木地块的低纬度区域漂移(Zhang Shihong et al., 2015; Zhao Guochun et al., 2018; Zhao Hanqing et al., 2021)。因此,我们认为正是由于这一时期华南板块的南移,可能导致其环境条件逐步向更适合埃迪卡拉生物分子生存的方向转变,为 *Aspidella* 和 *Shaanxilithes* 等典型的埃迪卡拉纪晚期生物分子在华南寒武系地层中得到了种群的延续提供了诱导因素,并参与了全球范围内的生命大爆发事件。而关于桃子冲组底部的时代,以及 *Aspidella* 和 *Shaanxilithes* 作为判断埃迪卡拉纪地层的标准化石,也值得我们在接下来的深入研究中继续进行讨论。

5 结论

(1) 本文首次在华南贵州清镇埃迪卡拉系—寒武系过渡地层桃子冲组下部的黑色硅质岩中发现了埃迪卡拉型 cf. *Aspidella* 盘状化石,是一类以同心圆环、中央凸起和凹痕为特征的圆盘。研究认为桃子冲组 cf. *Aspidella* 盘状化石是底栖软躯体后生生物的固着器结构,其形态、尺寸、分布和环境背景等与全球其他地区报道的埃迪卡拉纪盘状化石表现一致,并且排除了非生物过程作为阶梯状结构的来源。*Aspidella* 等埃迪卡拉纪软躯体生物分子具有利用氧气条件机会性繁殖发育的特点,清镇桃子冲组下部富氧、富营养的环境条件,也是其能够出现埃迪卡拉纪后生生物的原因之一。

(2) 固着器内部物质成分与基底围岩一致,均为富含 SiO_2 的沉积物,是清镇桃子冲组 cf. *Aspidella* 盘状化石保存的特征。我们倾向于认为桃子冲组 cf. *Aspidella* 盘状化石内部沉积物是在海水正常沉积作用下形成的,并没有生命过程的参与。并发现了盘状化石含 Fe、Al 物质的生物膜碎片,微生物菌落会生长并覆盖固着器的上表面,形成微生物席,将生物固着器粘在基底适当的位置稳定生长,茎干和复叶延伸到水体中。受到流速较快的单向边界流体影响,茎干与固着器的结合处被瞬间切断,没有出现水流拖曳茎干的现象。固着器结构受到微生物席的影响能够优先保存,而茎干和复叶却消失不见。黏土和砂砾的差异压实作用会在死亡后的生物固着器球壁上产生阶梯状的轮廓,固着器坍塌后的中空结构快速被沉降的砂砾填满,形成附着在覆盖层底部垂向凸起的阶梯状 cf. *Aspidella* 圆盘结构。

(3) 结合新元古代到古生代的全球古地理格局,华南板块持续地向华北、柴达木地块所处的低纬度区域漂移,环境的改变可能是 *Aspidella* 和 *Shaanxilithes* 等典型的埃迪卡拉纪晚期生物分子在华南寒武系地层中得到种群延续的诱导因素,并参与了全球范围内的生命大爆发事件,这对完善全球古地理背景进一步提供了生物学认识。

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First discovery of the Ediacaran-type discoid fossils at the bottom of Cambrian in Qingzhen, Guizhou: Biological, taphonomic and palaeogeographic implications

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Objectives: Discoid fossils are the earliest and the most important components in the Ediacaran biota. *Aspidella*, a disk-like Ediacaran form genus, is a typical fossil in Ediacaran sediments distributed worldwide. This article describes the Ediacaran biota element *Aspidella* disc-like fossil (cf. *Aspidella*) which is here first recorded in siliceous rocks at the bottom of the Taozichong Formation of the Ediacaran – Cambrian transitional strata in Qingzhen of Guizhou, and studies its biological and ecological characteristics, as well as its preservation mechanism in the Cambrian strata. This is crucial for the rebuilding of the ecosystem during the Ediacaran – Cambrian

transition and for the understanding of the early evolution of organisms during the "Cambrian Explosion of life".

Methods: In this article, the 3D view image of fossils was taken using the Leica-DVM6 3D microscopy system. And the micromorphological observations and microchemical analysis of fossils were performed using a HITACHI-SU8010 scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS). The mineral composition of the fossil was analyzed by whole rock X-ray diffraction (XRD, PANalytical B. V.) and Raman spectroscopy (LabRAM HR Evolution).

Results: Ediacaran biota element *Aspidella* disc-like fossil (cf. *Aspidella*) which is here first recorded in siliceous rocks at the bottom of the Taozichong Formation of the Ediacaran - Cambrian transitional strata in Qingzhen of Guizhou as a disc characterized by concentric ring, central bulge and indentation. A 3D image of the *Aspidella* fossil shows obvious step-like layer changes. In summary, according to the SEM—EDS analysis, combined with the in situ Raman spectroscopy and the XRD analysis, cf. *Aspidella* is the morphological remains of holdfasts of organisms on the seabed, rather than geological sedimentary phenomena such as solid fossils or gas escape structures. Its special ring structures are formed by the rapid filling of holdfasts by sand and clay minerals during the process of burial and mutation.

Conclusions: We tend to think that cf. *Aspidella* of Taozichong Formation is the holdfast of benthic soft-body phylloids, and its internal sediments are formed by normal sedimentation of seawater. Fragments of holdfast biofilm containing Fe and Al substances have been found. It is confirmed that the holdfast was preferentially preserved by a microbial mat, while the stem and compound leaves disappeared, and differential compaction of clay and sand produced a stepped profile on the bulb wall of the holdfast after death. Based on the similarity between the bioassemblages in the Ediacaran - Cambrian Taozichong Formation of South China and the Ediacaran in the North China and Qaidam blocks, and the global paleogeographic pattern during the transition period from Ediacaran to Cambrian, the South China Plate have moved continuously from the middle latitudes to the low latitudes of the North China and Qaidam blocks. Environmental changes may have induced the population continuation of late Ediacaran biota elements in the South China Cambrian strata, and further expanding the temporal and spatial distribution of classic Ediacaran-type fossils in geological history.

Keywords: cf. *Aspidella*; Holdfast; Ediacaran biota; Taphonomy; Cambrian; Sinian

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