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河南寒武系遗迹化石 *Thalassinoides* 及其沉积环境控制因素

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摘要 【目的】河南寒武系发育大量遗迹化石 *Thalassinoides*, 通过研究遗迹种的不同形态和分布特征, 分析其沉积环境控制因素。【方法】基于沉积学和遗迹学研究, 将该区 *Thalassinoides* 形态、大小、扰动深度、扰动强度等特征与沉积环境参数相结合。【结果】密集分布的Y-形分支、分支处膨大的二维潜穴 *Thalassinoides suevicus* 发育在水体动荡氧气充足的潮间带; 稀疏分布的Y-形长分支、直径大的二维潜穴 *Thalassinoides horizontalis* Type 1 形成于水体动荡、氧气充足、营养物质丰富的鲕粒滩前浅水区; 较密集分布的T-形分支、分支短直径小的二维潜穴 *Thalassinoides horizontalis* Type 2 形成在鲕粒滩前深水区; 具有垂直管道、多分支且发育厚衬壁的三维箱状潜穴 *Thalassinoides bacae* 则发育在氧和营养物质均匮乏的滩间局限海和深水潮下带。【结论】*Thalassinoides* 不同遗迹种及形态的变化受控于沉积环境的水深、水动能、营养物质和氧含量等因素, 造迹生物采取不同的策略以应对变化的沉积环境。

关键词 寒武纪; 碳酸盐岩台地; 生物扰动; 沉积环境

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0 引言

遗迹化石是造迹生物与沉积底质相互作用的产物, 其造迹生物的非限定性、原地保存性、量大且易于识别等特征, 使得遗迹化石成为探索古生物和古环境相互作用的有力工具(Knaust and Bromley, 2012; 齐永安等, 2012; 罗茂等, 2021; 许晴旻等, 2023)。特别是穴居生物对其栖息地环境变化反应敏感, 因此, 在很多情况下, 遗迹化石比实体化石更能反映沉积环境条件(Wetzel and Rodríguez-Tovar, 2021)。遗迹化石的种属、丰度、个体大小、穿透沉积物的深度、潜穴壁的光滑度和结构等, 均具有较高的环境指示意义(Wetzel and Rodríguez-Tovar, 2021)。例如, 个体细小的、浅层分布的规则图案状的潜穴系统通常反映安静缺氧的深水环境(Uchman and Wetzel, 2012), 而个体较大、形态简单、丰度高的垂直

潜穴一般代表动荡富氧的浅水环境(Buatois and Mángano, 2004, 2011); 潜穴壁光滑通常指示沉积底质具有一定的固结度(Knaust, 2021)。遗迹化石 *Thalassinoides* Ehrenberg(1944)是最古老的复杂遗迹化石, 地史分布从寒武纪至今(Jin *et al.*, 2012, 2013; Knaust, 2021), 但主要集中在中生代和新生代(Bromley and Ekdale, 1984; Carmona *et al.*, 2004; El-Sabbagh *et al.*, 2017)。其典型特征是具有大量T-形或Y-形分支的网状或三维箱状开放潜穴系统。*Thalassinoides* 在多种岩性中均可发育, 包括灰岩、白云岩、砂岩、粉砂岩和泥岩(Sheehan and Schiefelbein, 1984; Joseph *et al.*, 2012; Sharafi *et al.*, 2012; Leonowicz, 2015; Marusin *et al.*, 2022), 广泛应用于沉积环境解释(Ekdale and Bromley, 2003; 李凯楠等, 2019; Knaust, 2024; Zhang *et al.*, 2024)和海洋底栖生态系统工程研究中(McIlroy and Logan, 1999;

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Solan and Kennedy, 2002; Erwin, 2008; Liu *et al.*, 2024)。

河南寒武系发育大量的 *Thalassinoides*, 地层跨度从寒武系黔东统都匀阶朱砂洞组到芙蓉统排碧阶固山组, 形态特征从二维网状到三维箱状展布, 同时伴有潜穴结构、直径、大小、扰动强度、扰动深度等的变化。本文通过对河南富含 *Thalassinoides* 的地层沉积学特征及对应的不同遗迹种的特征研究, 探索 *Thalassinoides* 不同遗迹种与沉积环境之间的关系, 为更好地利用 *Thalassinoides* 解释古环境及重建寒武纪古生态提供支撑材料。

1 地质背景

寒武纪华北板块位于赤道附近, 是一个被泛海洋包围的孤立克拉通(图 1a, Torsvik and Cocks, 2019)。寒武纪之初华北板块为古陆, 长期遭受风化剥蚀, 黔东世都匀期被水淹没开始接受沉积(冯增昭等, 1989, 2004; 裴放等, 2008), 整体表现为西高东低、南高北低的古地理格局, 且以开阔台地相、浅滩和潮坪沉积为主(牟传龙等, 2016)。华北板块南部河南省寒武系除了缺失底部纽芬兰统和黔东统筇竹寺阶外, 其余地层出露良好且连续, 自下而上沉积了

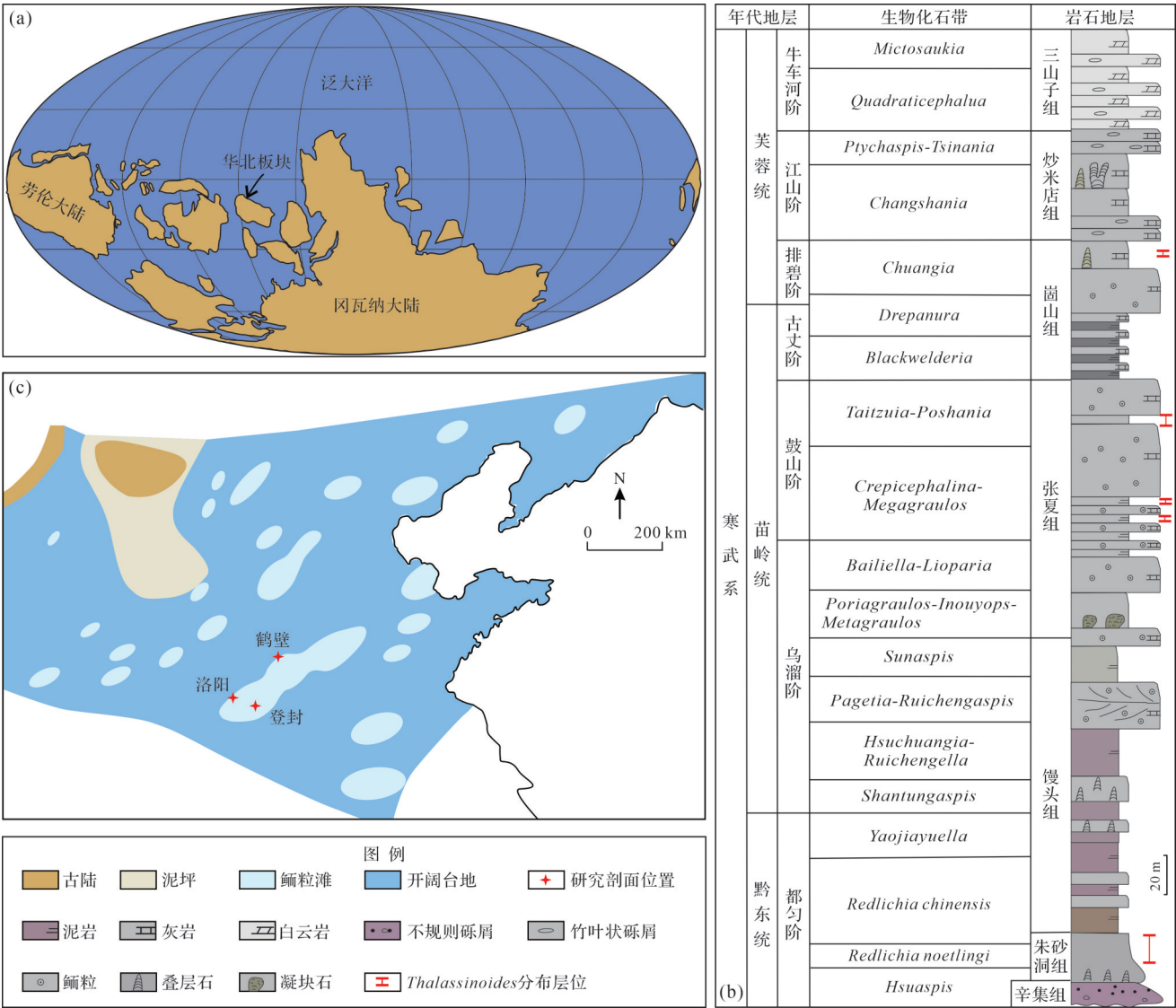


图 1 (a)寒武纪苗岭世华北板块的古地理位置(据 Torsvik and Cocks, 2019 修改); (b)河南寒武纪的综合地层图(据裴放, 2000; 朱茂炎等, 2019 修改); (c)寒武纪苗岭世华北板块的古地理格局(据冯增昭等, 2002 修改)

Fig.1 (a) Paleogeographic location of the North China Block in the Cambrian Miaolingian (modified from Torsvik and Cocks, 2019); (b) synthetical strata of the Cambrian in Henan (modified from Pei, 2000; Zhu *et al.*, 2019); (c) paleogeographic pattern in the Cambrian Miaolingian of the North China Block (modified from Feng *et al.*, 2002)

黔东统辛集组、朱砂洞组和馒头组下段,苗岭统馒头组上段、张夏组和崮山组下段,以及芙蓉统崮山组上段、炒米店组和三山子组(图1b)。本文遗迹化石 *Thalassinoides* 的主要剖面位置分布在河南省登封朱砂洞组、洛阳张夏组和鹤壁崮山组(图1c)。

2 研究方法

对发育 *Thalassinoides* 的地层进行详细的观察与测量,识别出重要的沉积学和遗迹学特征。沉积学特征主要包括岩性和岩性组合、沉积构造、沉积微相和伴生的生物成因沉积构造等。遗迹学特征主要包括遗迹化石的形态、产状、直径、扰动深度、填充物、衬壁的发育情况、生物扰动强度等。其中,生物扰动强度的划分依据 Droser and Bottjer(1986)提出的生物扰动指数(BI):生物扰动构造对原始沉积组构的改造程度的比例,划分为6个等级,分别对应不同的扰动量:1(0%),2(1%~10%),3(10%~40%),4(40%~60%),5(>60%),6(100%)。

3 *Thalassinoides* 沉积学及遗迹学特征

3.1 登封朱砂洞组

3.1.1 沉积学特征

登封朱砂洞组厚35.2 m,根据岩性特征分为三段(图2):底部一段厚7.2 m,以浅黄灰色膏溶角砾岩开始,角砾的大小不等,成分为具水平纹层的灰岩(图2a);向上过渡到浅灰色厚层具水平纹层的灰质白云岩(图2b,c),夹一层侧向不连续的叠层石丘(图2b底部);最上部为一层发育小型低角度交错层理的细颗粒灰岩(图2e),显微镜下显示颗粒具有一定的分选性和磨圆度(图2f)。中部二段厚14.5 m,主要为深灰色厚层豹斑灰岩(图3),发育大量的遗迹化石 *Thalassinoides suevicus*。风化面上豹斑呈深灰色或土黄色,凸出于层面之上;基质呈灰白色;使用浓度5%的稀盐酸滴在风化面上,豹斑起泡微弱,而基质部分起泡剧烈;中间夹5层竹叶状砾屑灰岩,砾屑呈扁平状,定向性不明显(图2d)。顶部三段厚13.5 m,主要为浅灰色藻纹层灰质白云岩(图2g,h)夹浅紫红色灰质泥岩,白云岩中发育鸟眼构造。

3.1.2 遗迹学特征

二段的豹斑构造主要起因于生物扰动构造 *Thalassinoides suevicus*。*T. suevicus* 为在层面上多分

支的潜穴系统(图3a,b),分支角度以Y-形分支为主。潜穴直径通常为3~8 mm,且在分支点处呈现明显的膨大,膨大处一般宽10~13 mm。*T. suevicus* 常密集分布,布满整个层面,潜穴之间的交叉和叠覆现象常见。剖面上呈现出不规则的斑状构造,偶见分支现象(图3d),扰动深度较浅,一般不超过3 cm(图3c,d)。潜穴的填充物通常呈现出灰色(图3a)、土黄色(图3b,d)和深灰色(图3c),与浅灰色的围岩形成较为鲜明的对比。显微镜下观察潜穴填充物以细晶白云石为主,而围岩为泥晶方解石,且潜穴与围岩的边界清晰(图3e,f)。生物扰动指数BI为2~5(图3a~d),常见3~4,在二段的中部最强(图2)。

3.2 洛阳张夏组

3.2.1 沉积学特征

洛阳张夏组厚133 m,根据岩性特征分为四段(图4)。底部一段厚15.8 m,主要由浅灰色薄板状灰岩与极薄层状泥岩组成(图4a),中间夹四层竹叶状砾屑灰岩(图4a)。下部二段厚20.2 m,主要为微生物岩和生物扰动灰岩(图4b,c)及一层夹有薄层泥晶灰岩的鲕粒灰岩,生物扰动构造为 *Balanoglossites triadicus*。微生物岩主要为叠层石(图4b)和凝块石(图4c,d)。中部三段厚35 m,为颗粒灰岩和生物扰动灰岩互层(图4e,f),生物扰动构造为 *Thalassinoides horizontalis*(图5)。上部四段厚62 m,以厚层状鲕粒灰岩为主(图4g),夹数层侧向不连续的生物扰动灰岩(图4g);鲕粒灰岩的鲕粒大小均匀,多呈放射状纹层结构,颗粒接触,胶结物为亮晶方解石(图4h)。

3.2.2 遗迹学特征

张夏组发育大量的遗迹化石,其中 *Thalassinoides horizontalis* 分布在三段下部, *Thalassinoides bacae* 分布在四段上部。*Thalassinoides horizontalis* 的形态特征表现为层面多分支的二维潜穴。根据分支形态、分支间距和潜穴直径的不同,分为两个类型。*T. horizontalis* Type 1(图5a),为Y-形分支,分支间距较长,2~30 cm,多为15~30 cm,直径8~12 mm,层面上呈稀疏的管状结构,没有交叉和叠覆,扰动强度低,一般为2;分布在薄板状灰岩的层面上,不同层之间的潜穴个体和形态差别不大(图5b)。与 *T. horizontalis* Type 1伴生的有大量的生物碎屑,碎屑个体较大,主要为三叶虫碎片。*T. horizontalis* Type 2分布在 *T. horizontalis* Type 1之上的地层和较厚层灰

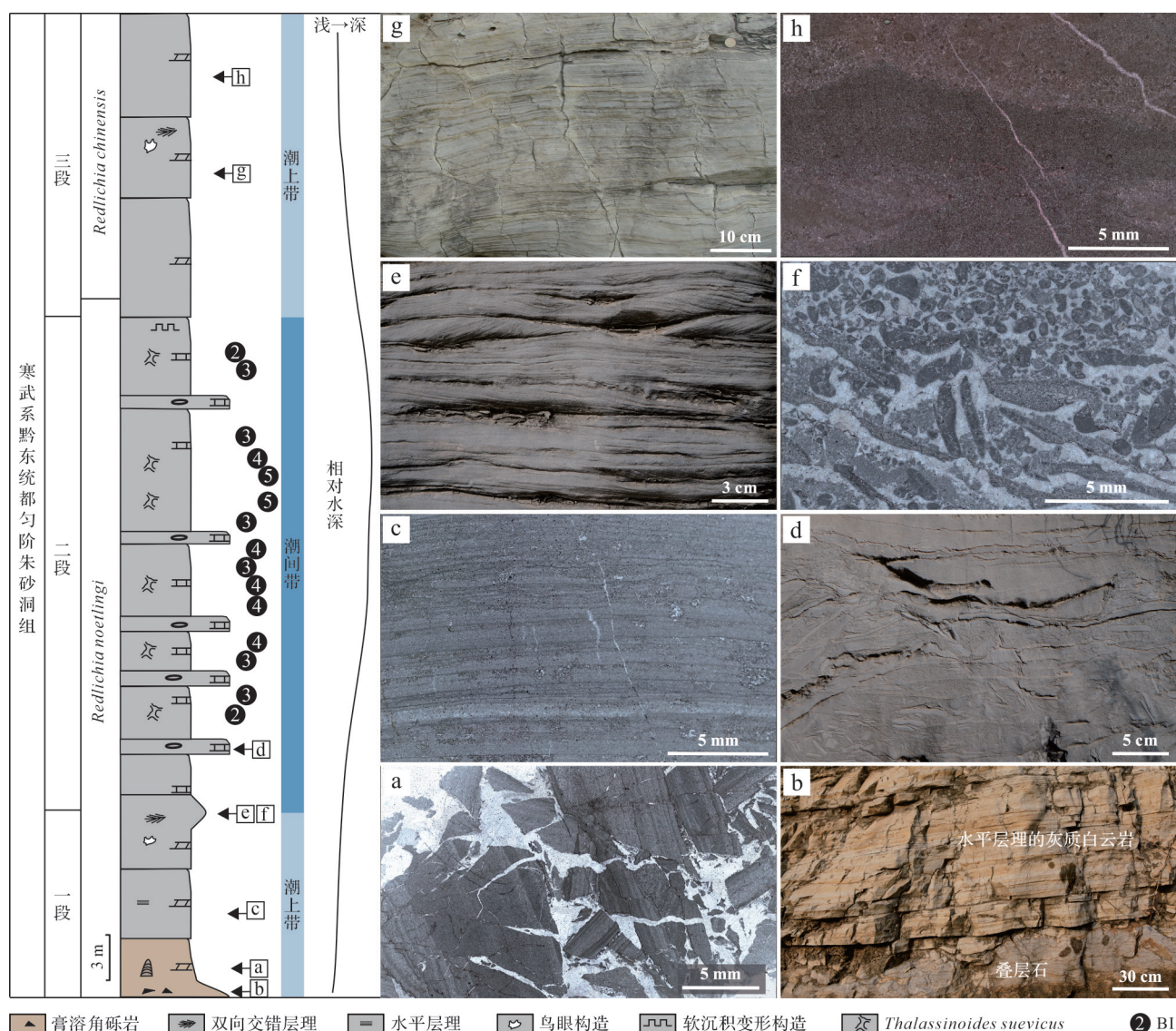


图2 登封地区朱砂洞组综合柱状图及野外和显微镜照片

(a)膏溶角砾岩;(b)叠层石及灰质白云岩;(c)水平纹层状灰质白云岩,单偏光;(d)竹叶状砾屑灰岩;(e)双向交错层理细颗粒灰岩;(f)细颗粒灰岩,单偏光;(g)纹层状灰质白云岩;(h)灰质白云岩,茜素红染色,单偏光

Fig.2 Synthetical strata, field and microscopic photos of Zhushadong Formation in Dengfeng area

(a) gypsum karst breccia; (b) stromatolite and calcite dolomite; (c) laminated calcite dolomite, plane-polarized light (PPL); (d) flat-pebble conglomerate; (e) bimodal cross-bedding fine grained limestone; (f) fine grained limestone, PPL; (g) laminated calcite dolomite; (h) calcite dolomite, staining of alizarin red, PPL

岩层面上,呈T-形分支,分支间距小,单支长度2~4 cm,潜穴直径为7~8 mm,层面上呈现网状结构(图5c),生物扰动强度高,BI为3,且潜穴管内常伴生有铁矿化作用(图5d);围岩为较细的泥晶方解石(图5d)。*Thalassinoides bacae*分布在四段顶部鲕粒灰岩之间的薄层泥晶灰岩中,呈现多分支、具多个垂直管道的箱状潜穴系统(图5e~g),水平截面上多成圆点状或长条带状,偶有分支(图5g),剖面上呈倾斜的或垂直的管状、椭圆状等(图5e,f),扰动深度较深,约为15 cm;潜穴具有较厚的衬壁,衬壁为极细的泥晶方

解石,衬壁外面通常围绕着白云石晕圈,而围岩由较细的泥晶方解石组成(图5h)。

3.3 鹤壁崮山组

3.3.1 沉积学特征

鹤壁崮山组厚21 m,根据岩性特征分为三段(图6),下部一段厚12.1 m,主要为浅灰色—深灰色薄层泥晶灰岩与灰黄色泥岩互层(图6a,e),夹数层竹叶状砾屑灰岩和薄层鲕粒灰岩(图6b),薄层泥晶灰岩中含有极其细小的遗迹化石 *Mycellia* (图6c)和极其细小的生物碎屑(图6f),黄色泥岩层面上有三叶虫

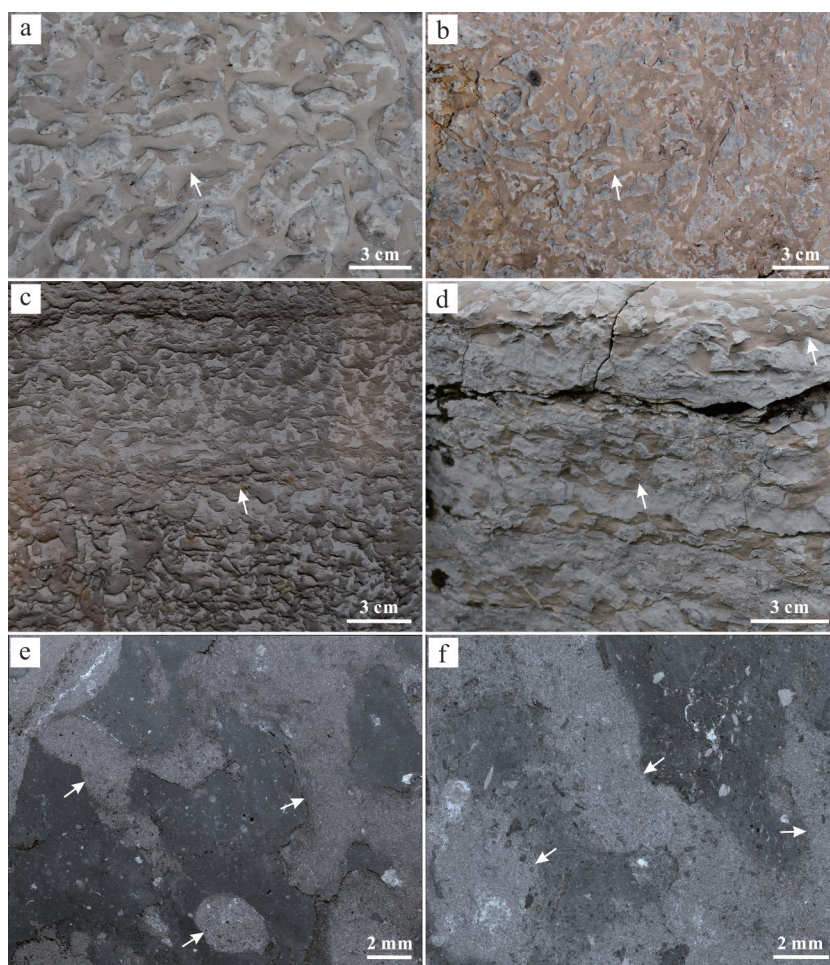


图3 登封地区朱砂洞组 *Thalassinoides suevicus* 野外和显微镜照片

(a)层面上的大量 *T.suevicus*, 填充物为灰色, BI为3; (b)层面上的大量 *T.suevicus*, 填充物为土黄色, BI为4; (c)剖面上的 *T.suevicus*, 填充物为深灰色, BI为5; (d)剖面上的 *T.suevicus*, 填充物为土黄色, BI为2; (e, f)含 *T.suevicus* 的灰岩, 单偏光, 白色箭头指示 *T.suevicus*

Fig.3 Field and microscopic photos of *Thalassinoides suevicus* from the Zhushadong Formation in the Dengfeng area

(a) large number of *T.suevicus* in the bedding plane, with gray filling, BI is 3; (b) large number of *T.suevicus* in the bedding plane, with earthy yellow filling, BI is 4; (c) *T.suevicus* in a vertical section, with dark gray filling, BI is 5; (d) *T.suevicus* in a vertical section, with earthy yellow filling, BI is 2; (e, f) limestone containing *T.suevicus*, PPL, the white arrows mark the *T.suevicus*

碎片(图6d)和黄铁矿晶体(图6f)。中部二段厚5.5 m, 主要为竹叶状砾屑灰岩, 鲕粒灰岩和浅灰色叠层石丘灰岩, 叠层石丘横向上不连续, 以大型柱状结构为主, 具抗浪格架, 柱间充填大颗粒碎屑, 底部有厚度不均匀的砾屑层。上部三段厚3.4 m, 为深灰色生物扰动泥晶灰岩夹极薄灰黄色泥线(图6e), 发育多层砾屑灰岩和微生物丘灰岩(图6g, h)。

3.3.2 遗迹学特征

鹤壁崮山组三段薄层泥晶灰岩中发育 *Thalassinoides bacae*。 *T. bacae* 作为单一遗迹属种占领地层, 在层面上呈串珠状(图7a)或稀疏的管状突起(图7b), 以Y-形分支为主(图7c), 含有少量T-形分支(图7c)。 *T. bacae* 发育厚衬壁, 露头暴露在外长期遭

受风化作用使得晕圈和填充物被完全剥蚀, 剖面上衬壁更加突出(图7d)。潜穴直径为5~8 mm。 *T. bacae* 在层面和剖面上的扰动指数较低, BI为2~3, 扰动深度一般小于5 cm。显微镜下观察到填充物和晕圈以细晶白云石为主, 衬壁和围岩成分为微晶方解石(图7e, f)。

4 讨论

同一遗迹属通常是同一类造迹生物或者营相同生态习性的生物所建造(Seilacher, 2007), 而遗迹种的不同, 一般受底质性质、沉积速率、水动力条件、营养物质和氧含量等多方面因素影响(Taylor *et al.*, 2003; Feng *et al.*, 2019)。 *Thalassinoides* 作为浅海沉

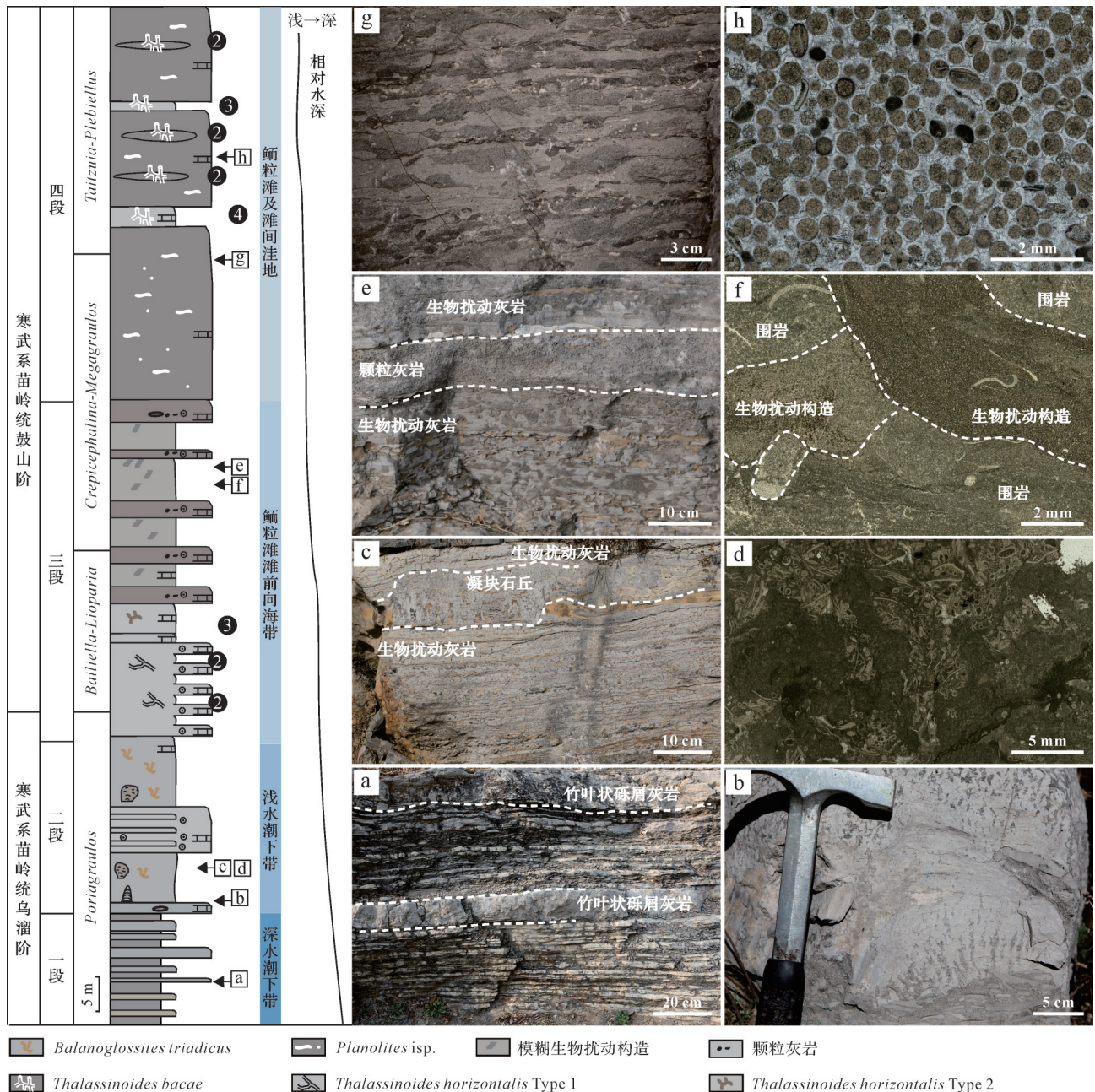


图4 洛阳地区张夏组综合柱状图及野外和显微镜照片

(a)薄板状灰岩与泥岩夹竹叶状砾屑灰岩;(b)叠层石灰岩;(c)生物扰动灰岩夹凝块石丘;(d)凝块石,单偏光;(e)颗粒灰岩和生物扰动灰岩;(f)生物扰动灰岩,单偏光;(g)厚层鲕粒灰岩和生物扰动灰岩;(h)鲕粒灰岩,单偏光

Fig.4 Synthetical strata, field and microscopic photos of Zhangxia Formation in Luoyang area

(a) laminated limestone and mudstone with flat-pebble conglomerate; (b) stromatolite limestone; (c) bioturbated limestone with thrombolites; (d) thrombolites, PPL; (e) grainstone and bioturbated limestone; (f) bioturbated limestone, PPL; (g) thick-bedded oolitic limestone and bioturbated limestone; (h) oolitic limestone, PPL

积中常见的遗迹化石,其遗迹种或形态的细微变化与沉积环境有密切的关系(Knaust, 2024; Zhang *et al.*, 2024)。河南寒武系数套地层中均发育 *Thalassinoides*,共包括三个遗迹种的四个形态类型,将其与所在的沉积环境相结合,探究两者之间的关系。

登封朱砂洞组一段主体岩性为灰岩和灰质白云岩,发育水平纹层,底部的膏溶角砾岩是暴露在干旱的条件下又经大气降水淋滤而形成(彭勇民等, 2012),低角度双向交错层理是潮汐作用的产物,表明该段形成在潮上带。二段为一套生物扰动灰岩,夹竹叶状砾屑灰岩,形成在完全水下的潮间带,时常

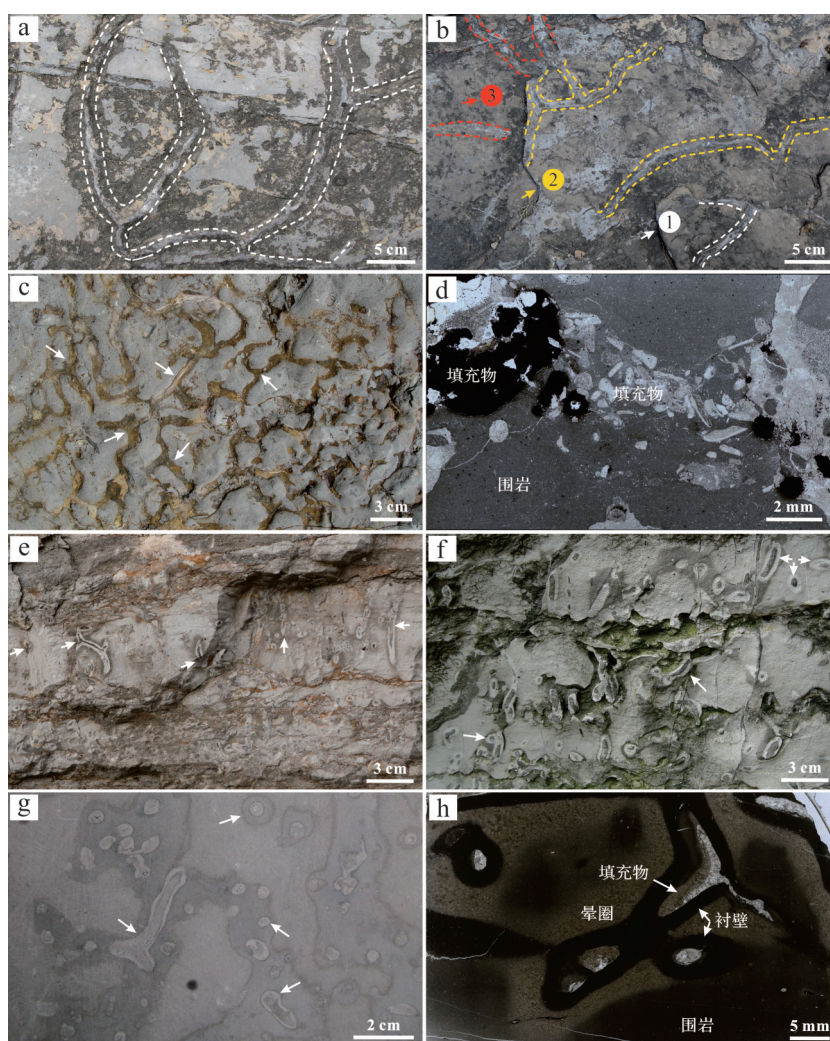


图5 洛阳地区张夏组 *Thalassinoides* 野外和显微镜照片

(a)层面上的 *T. horizontalis* Type1, 白色虚线示意, BI 为 2; (b)三个层位的 *T. horizontalis* Type1, 虚线示意, 不同颜色代表不同层的遗迹化石, BI 为 2; (c)层面上的 *T. horizontalis* Type2, 土黄色的填充物, BI 为 3; (d) *T. horizontalis* Type2 的显微照片, 显示填充物为颗粒较粗, 部分发生铁矿化作用, 围岩为泥晶方解石; (e)剖面上的 *T. bacae*, 显示垂向扰动深度大, 局部有分支现象, BI 为 2; (f)剖面上的 *T. bacae*, BI 为 3; (g)层面上的 *T. bacae*, BI 为 3; (h)含 *T. bacae* 的灰岩, 可清晰地看到潜穴填充物、衬壁、晕圈和围岩的成分差别, 单偏光

Fig.5 Field and microscopic photos of *Thalassinoides* from the Zhangxia Formation in the Luoyang area

(a) *T. horizontalis* Type1 in the bedding plane indicated by the white dotted line, BI is 2; (b) *T. horizontalis* Type1 in three beds, indicated by the dotted line, different colors represent different beds of trace fossil, BI is 2; (c) *T. horizontalis* Type2 in the bedding plane, earthy yellow filling, BI is 3; (d) microscopic photo of *T. horizontalis* Type2, the filling material is coarse, part of it is iron-mineralized, and the surrounding rock is micrite calcite; (e) *T. bacae* in a vertical section, the vertical disturbance depth is large with localized branching, BI is 2; (f) *T. bacae* in a vertical section, BI is 3; (g) *T. bacae* in the bedding plane, BI is 3; (h) limestone containing *T. bacae*, the composition difference of burrow filling, lining, halo, and surrounding rock can be clearly seen, PPL

受到风暴影响。*Thalassinoides suevicus* 呈现浅阶层特征、密度极高、叠覆现象普遍, 指示营养物质和含氧量充足的环境, 大量的造迹生物在沉积物浅层挖掘潜穴、进食 (Griffis and Suchanek, 1991; Dworschak and Rodrigues, 1997)。潜穴形态不规则, 且潜穴边界与围岩较为清晰, 结合竹叶状砾屑灰岩的出现, 说明表层沉积物具有一定的固结性 (Ekdale and Bromley, 2003; Ekdale and Lamond, 2003)。三段藻纹层灰质

白云岩夹浅紫红色灰质泥岩, 发育鸟眼构造, 说明水体变浅, 蒸发作用强, 为潮上带。

华北板块在张夏期早期发生最大的海侵事件, 然后进入强迫型海退阶段 (冯增昭等, 2004)。洛阳张夏组一段深灰色泥岩和页岩发育, 缺乏生物扰动, 偶尔有竹叶状砾屑层, 表明沉积环境为潮下带深水区, 水深在风暴浪基面附近, 总体上水体能量较低, 但偶尔受到风暴的影响。二段以富含生物碎屑的微

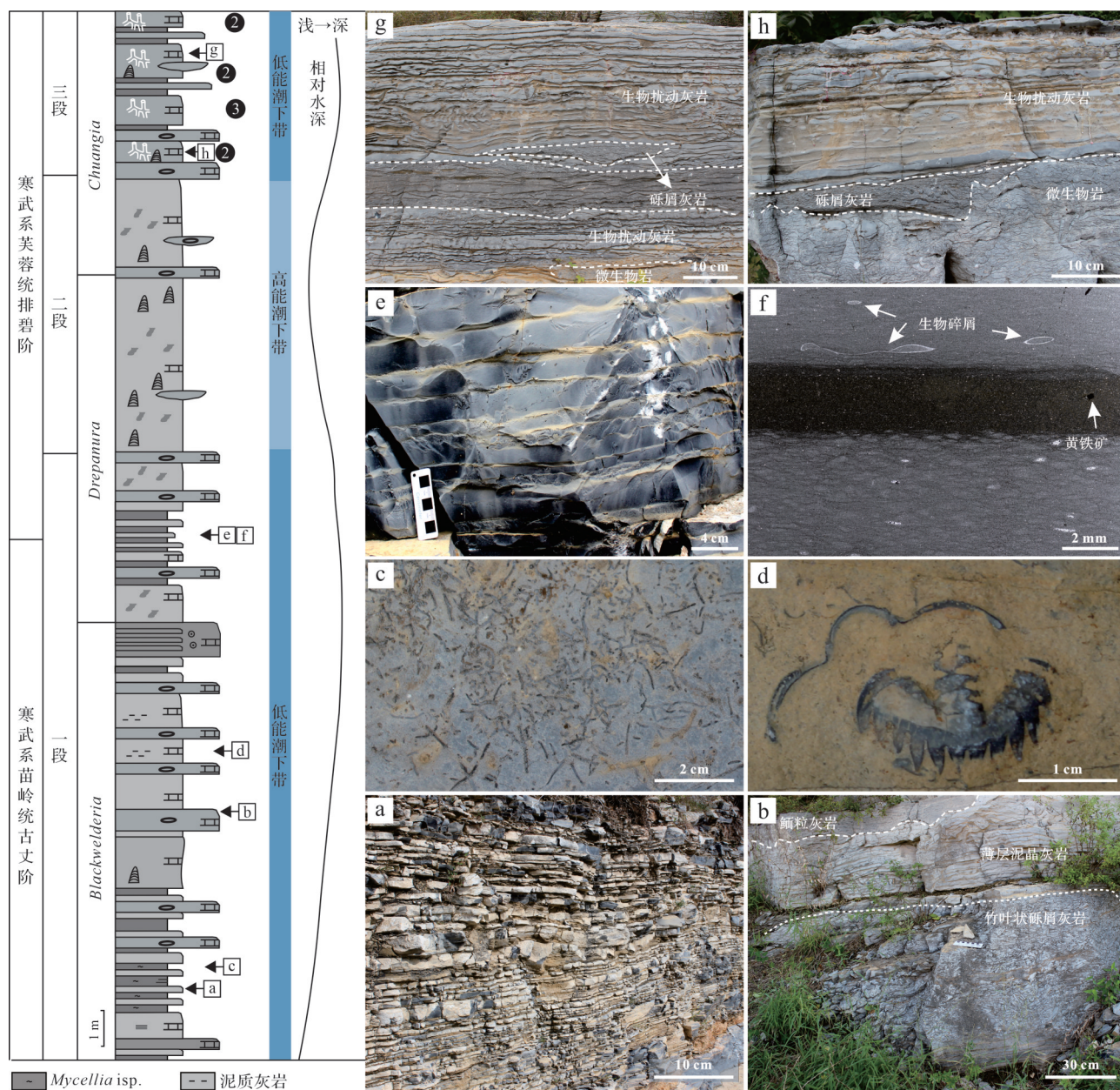


图6 鹤壁地区崮山组综合柱状图及野外和显微镜照片

(a)浅灰色灰岩与灰黄色泥岩互层;(b)砾屑灰岩、泥晶灰岩和鲕粒灰岩;(c)细小遗迹化石 *Mycellia* isp.;(d)泥岩层面上的三叶虫碎屑;(e)深灰色薄层泥晶灰岩;(f)泥晶灰岩和泥岩,单偏光;(g,h)生物扰动灰岩、颗粒灰岩和微生物岩

Fig.6 Synthetical strata, field and microscopic photos of the Gushan Formation in the Hebi area

(a) light gray limestone and grayish yellow mudstone interlayer; (b) conglomerate, micrite, and oolitic limestone; (c) tiny trace fossil *Mycellia* isp.; (d) trilobite debris on mudstone in the bedding plane; (e) dark gray thin-bedded micrite; (f) micrite and mudstone, PPL; (g, h) bioturbated limestone, grainstone, and microbialite

生物岩和含有少量 *Balanoglossites triadicus* 的扰动灰岩为主,说明水体深度变浅,水体氧含量有所增加,为潮下带浅水区。三段下部是颗粒灰岩和富含 *Thalassinoides horizontalis* Type 1 的薄板状灰岩,形成环境为鲕粒滩的滩前浅水区,水动力条件强,常受波浪或湍流的影响,从而改善了水体循环,带来氧气和营养物质等,形成直径更大,潜穴管更长的洞穴系统,且沉积速率快,生物尚未对沉积物进行充分扰

动。而 *Thalassinoides horizontalis* Type 2 保存在较厚层状微晶灰岩中,该层生物碎屑少,生物扰动强度大,但是潜穴个体较 *Thalassinoides horizontalis* Type 1 小,分支的距离小,潜穴壁更加光滑,说明沉积环境较稳定,殖居窗长(Ekdale and Bromley, 2003)。沉积速率缓慢,生物可对沉积物进行长时间的扰动,且沉积底质具有一定的固结性(Scholle and Ulmer-Scholle, 2003; Rodríguez-Tovar *et al.*, 2017; Wang *et*

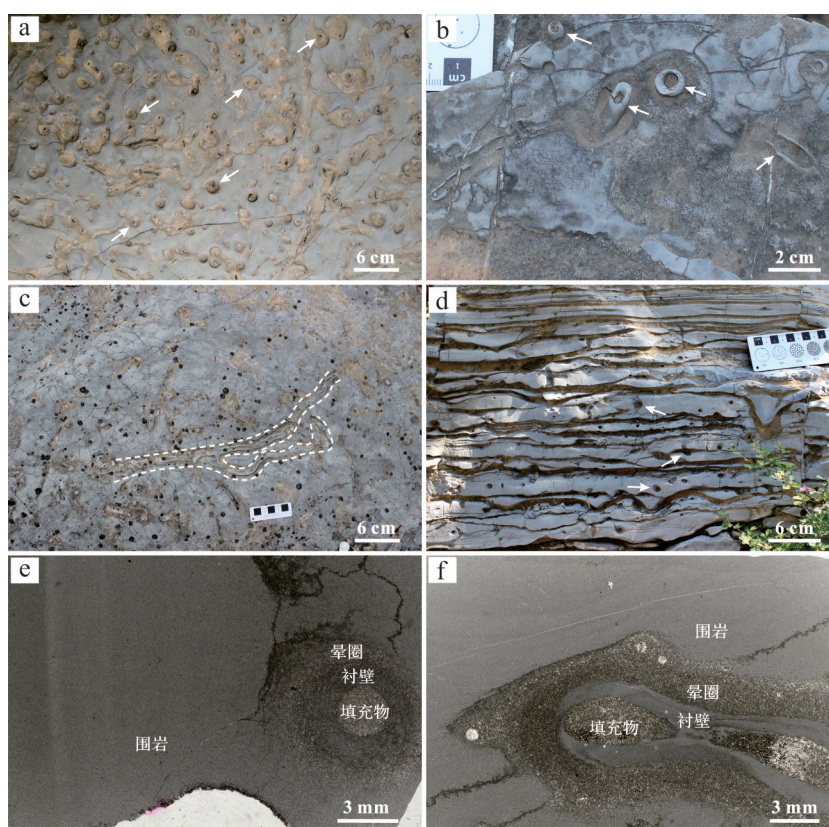


图7 鹤壁地区崮山组 *Thalassinoides bacae* 野外和显微镜照片

(a~c)层面上的 *T. bacae*; (d)剖面上的 *T. bacae*; (e, f)含 *T. bacae* 的灰岩,可清晰地看到潜穴充填物、衬壁、晕圈和围岩的成分差别,单偏光

Fig.7 Field and microscopic photos of *Thalassinoides bacae* from the Gushan Formation in the Hebi area

(a~c) *T. bacae* in the bedding plane; (d) *T. bacae* in a vertical section; (e, f) limestone containing *T. bacae*, the composition difference of burrow filling, lining, halo and surrounding rock can be clearly seen, PPL

al., 2019)。其形成环境位置较 *T. horizontalis* Type 1 略深,水体动能略低,氧含量降低。

洛阳张夏组顶部四段以厚层鲕粒灰岩为主,鲕粒的分选性好,鲕粒间为亮晶方解石胶结,说明形成在持续高能动荡的鲕粒滩环境。*T. bacae* 发育在厚层鲕粒灰岩的微晶灰岩夹层中,且有些夹层横向上呈向下凹的透镜体状,说明其形成环境与鲕粒滩关系密切,可能为高能鲕粒滩的滩间局限海,属于半封闭环境,水体较安静且氧含量低。*T. bacae* 垂向管道多且较深,向下延伸到一定深度后分支,形成复杂的三维箱状结构。潜穴有致密且较厚的衬壁体现了造迹生物具有极强的建造潜穴能力以及适应营养物质和氧气匮乏的能力(Ekdale and Bromley, 2003; 李凯楠等, 2019)。

鹤壁崮山组一段主要为浅灰色—深灰色薄层泥晶灰岩与灰黄色泥岩互层,是潮下带深水环境的产物,而极其细小的遗迹化石 *Mycellia* 是典型低能缺氧环境中的代表,加之薄片普遍存在黄铁矿晶体,也

进一步证实了沉积环境的缺氧。二段竹叶状砾屑灰岩,鲕粒灰岩和叠层石丘灰岩,含生物扰动构造,说明二段的水体变浅,为潮下带浅水区。上部三段砾屑灰岩、微生物丘灰岩和含 *T. bacae* 的生物扰动灰岩,生物扰动强度较二段低,说明水体加深。尽管崮山组的 *T. bacae* 的形态特征与张夏组类似,但潜穴密度较张夏组低,可能由两者的沉积环境决定的,崮山组水深比张夏组上部深,含氧量较张夏组更低。

综上所述,河南寒武系 *Thalassinoides* 的形态变化与沉积环境有密切的关系,在氧气和营养物质充足的潮间带发育大量的 *T. suevicus*,而在沉积速率快、氧气和营养物质充足的鲕粒滩滩前环境则发育个体大、分支长的浅层水平潜穴 *T. horizontalis* Type 1; 随着水体向海略微加深,过渡到密集分支、直径较小的 *T. horizontalis* Type 2; 在半封闭的缺少营养物质和氧气的静水环境中是机会种生物建造的发育厚壁的 *T. bacae* (图8)。从寒武纪初期到寒武纪中后期, *Thalassinoides* 的形态逐渐变得复杂,从浅阶层到深阶

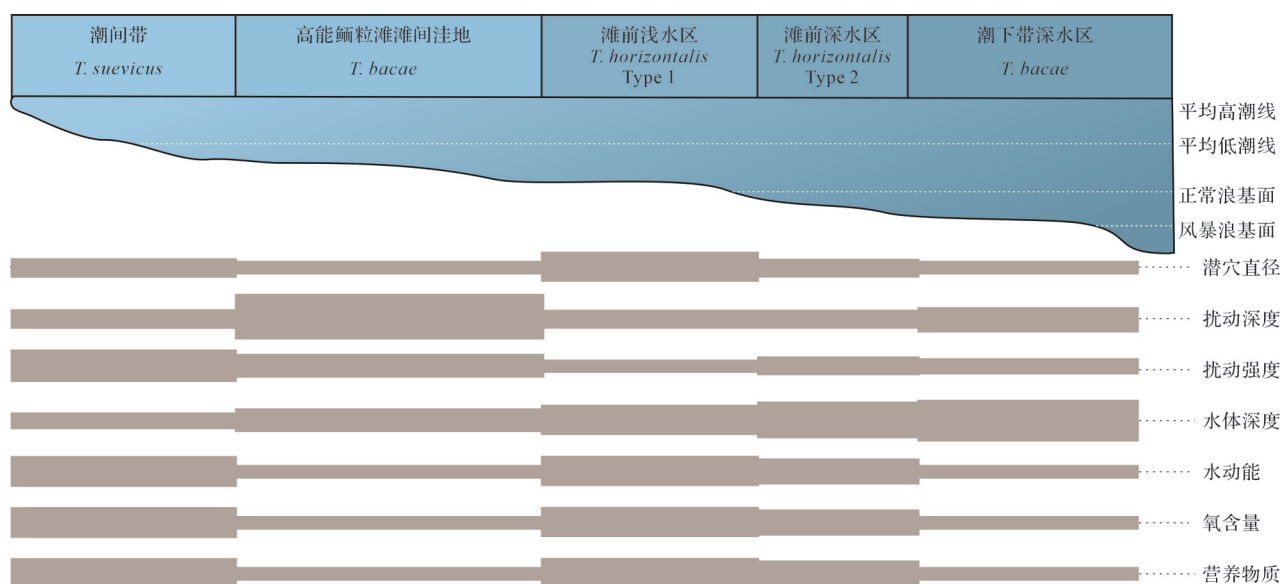


图8 河南寒武系不同形态的 *Thalassinoides* 与沉积环境的关系模式图

Fig.8 Relationship schematic model between different forms of *Thalassinoides* and various paleoenvironmental factors from the Cambrian in Henan province

层、从近表层的二维潜穴逐渐演变为复杂的三维潜穴系统、从没有衬壁到发育致密的厚衬壁,反映了造迹生物应对不同生存环境采取的建筑策略以及行为习性的进化。

5 结论

河南寒武系发育大量的 *Thalassinoides*, 共识别出了三个遗迹种的四个形态类型: 登封朱砂洞组的 *T. suevicus*, 洛阳张夏组的 *T. bacae*、*T. horizontalis* Type 1 和 Type 2, 鹤壁崮山组的 *T. bacae*。登封朱砂洞组 *T. suevicus* 是 Y-形分支的(分支处膨大)浅阶层网状潜穴系统, 密集分布, 形成于水体动荡、氧气和营养物质充足的潮间带。洛阳张夏组三段 *T. horizontalis* Type 1 以 Y-形分支、分支间距长、直径大为特征, 稀疏分布, 形成于水动力强, 氧气和营养物质丰富、沉积速率高的鲕粒滩的滩前浅水区, *T. horizontalis* Type 2 以 T-形分支、分支间距短、直径略小, 扰动强度大为特征, 形成于鲕粒滩的滩前较深水区。洛阳张夏组四段和崮山组三段的 *T. bacae* 为具有垂向管并发育厚衬壁的三维箱状潜穴系统, 扰动强度低到中等, 形成于半闭塞的滩间洼地、滩间局限海或缺氧的深水潮下带。

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Trace Fossil *Thalassinoides* and Its Paleoenvironmental Factors from the Cambrian in Henan Province

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Abstract: [Objective] A large number of *Thalassinoides* trace fossils developed in the Cambrian strata of Henan province. We studied the morphology and distribution characteristics of different ichnospecies and analyzed the sedimentary environment-controlling factors. [Methods] Based on lithology and ichnography, the morphology, size, disturbance depth, and disturbance intensity of *Thalassinoides* in this area were combined with sedimentary environment parameters. [Results] The dense network *Thalassinoides suevicus* features Y-shaped branches with enlarged intersections, developed in the intertidal zone where water is turbulent and oxygen is abundant. Sparse *Thalassinoides horizontalis* Type 1, which is Y-shaped long branches with large diameters, formed in the shallow water area in front of the oolitic beach with abundant oxygen and nutrients due to water turbulence. *Thalassinoides horizontalis* Type 2, T-shaped short branches with smaller diameters, occurred in deeper waters on the seaward side in front of the oolitic beach. The three-dimensional, boxwork burrows of *Thalassinoides bacae*, featuring vertical tubes, branches, and thick lining walls, developed in interbeach-confined seas and deep subtidal zones where oxygen and nutrients were deficient. [Conclusions] The variation in different ichnospecies and morphologies of *Thalassinoides* is controlled by factors such as water depth, water kinetic energy, nutrients, and oxygen content of the sedimentary environment. The trace maker adopted different strategies to cope with the changing sedimentary environment.

Key words: Cambrian; carbonate platform; bioturbation; sedimentary environment