

寒武纪早期微体化石上的异质体拖曳迹与微型 钻孔结构

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摘要 陕南西乡张家沟剖面的寒武纪宽川铺组中产出的磷酸盐化微体化石上大量保存了一种微型管道结构, 被解释为异质体拖曳迹(ambient inclusion trails, AITs). 同时报道并讨论了与化石相关的3种AITs新现象: (1) AITs及与其共生的钻孔蓝细菌和钻孔真菌化石. 通过直接对比揭示了三者形态和保存模式上的不同, 进一步澄清了区分类似结构的生物成因和非生物成因的标准. (2) 罕见的有机碳质的AITs末端推进颗粒. 常见的AITs一般是由黄铁矿颗粒的运移造成, 碳质末端颗粒的发现可以进一步丰富AITs成因和形态多样化的解释, 还得以通过碳质物的拉曼光谱地质温度计, 推测出化石群埋藏后经过了极低变质作用. (3) AITs在原牙形类化石上呈环绕分布. 根据AITs的形成机制对这一现象进行分析探讨, 从侧面佐证了原牙形类化石刺体的原始成分为有机质, 并且在成岩过程中经历次生磷酸盐化的观点.

关键词 AITs, 钻孔微生物, 碳质物拉曼光谱, 地质温度计, 原牙形类

异质体拖曳迹(ambient inclusion trails, AITs)是一种微观管状结构, 一般认为是由于岩体内的异质颗粒(最常见的是黄铁矿颗粒)在基质中运动而留下的痕迹, 而推动异质体运动的主要动力可能是有机物腐解释放的气体, 如甲烷, 二氧化碳等. 这些异质体如果保存在AITs孔道的末端, 一般就被描述为“末端推进颗粒”(terminal propelled grains)^[1]. 这一结构在不同的基质和时代的地质记录中广泛存在, 关于AITs最早的记录是在约35亿年前澳大利亚Warra-woona群中^[2]; 比较典型的还见于34亿年前澳大利亚Strelley Pool砂岩内^[3], 以及20亿年前美国明尼苏达州的Biwabik组和19亿年前加拿大Gunflint组的硅质岩中^[4]. 此外, AITs在新元古代晚期至寒武纪的磷酸

盐化石上也比较普遍, 例如贵州陡山沱组微体化石^[5,6]以及波兰寒武纪的甲壳类化石上明显的微管结构^[7]等等. 相对于遥远的太古代, 这一时期生物侵蚀扰动的现象愈发常见, AITs因其特殊的形态特征常常与钻孔微生物化石或捕食钻孔相混淆^[8~11]. 故在化石研究中进一步明确区分AITs和真实的生物成因的微型钻孔构造有重要意义. 本文通过仔细观察产出于陕南西乡张家沟剖面的寒武纪宽川铺组磷酸盐化石上的AITs, 并结合与其共生的两种钻孔微生物化石, 不仅深化了对三者形态学差异的认识, 更着重分析了微生物钻孔和AITs在形成阶段和保存模式上的不同, 为它们的识别提供了更为多样和可靠的参考依据. 此外, 一些和化石相关的新现象, 即碳质的

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AITs末端推进颗粒以及原牙形类化石上特殊的AITs分布规律也被观察描述,并对其古生物学意义进行了讨论.

1 区域地质背景与化石材料

本文研究的化石产出于陕西汉中西乡县河西乡的张家沟剖面.该剖面主要出露了寒武纪早期的宽川铺组,总厚度约为21 m,可以初步分为4层^[12].第2层为灰白色致密块状含磷生物灰岩,其上部化石最为富集.文中材料均采自该层位,其中以*Protohertzina anabarica*, *Canopoconus calvatus*, *Conotheca subcurvata*, *Olivoides multisulcatus*为主,可以与寒武纪第1小壳化石组合带(*Anabarites trisulcatus*-*Protohertzina anabarica*)的组成分子对比^[13],时代约为535 Ma,属于寒武纪纽芬兰世幸运期^[14,15].

样品主要以传统的醋酸酸蚀(8%~10%)处理取得,使用扫描电子显微镜(FEI Quanta 400F, 配备Oxford Instruments X射线能谱仪)进行细致形态观察,并辅以部分薄片和抛光切面.对于在部分AITs孔道末端发现的奇异球状颗粒使用Renishaw inVia共聚焦显微拉曼光谱仪分析其化学成分(514.5 nm Ar⁺离子激光器;测试功率20 MW;光栅狭缝20 μm;显微镜放大倍率目镜×10,物镜×50;测试范围150~2000 cm⁻¹).之后使用OriginPro 2016软件对球状颗粒的拉曼光谱进行分析,推测碳质物所经历的最高变质温度.

2 结果与讨论

2.1 AITs与钻孔微生物化石的区别

在宽川铺组磷酸盐化石上,除了广泛存在的AITs孔道,还共生有丰富的钻孔微生物化石(图1),这使得我们得以在同一个系统之内直接对比非生物成因和生物成因的结构(表1).

(i) 形态特征区别. 研究材料中发现的钻孔微生物化石主要有2种:(1)单独的细长的圆柱状丝体,丝体直径约为5.5~7.5 μm,长度变化较大,未见明确的始末终端,观察所见最长为300 μm.保存较好的标本中,丝体呈现明显的念珠状,沿线和末端均有球状膨大体,直径可达9 μm.丝体不分叉,但可以互相交叠,也有比较密集的网状集群.所有丝体均平行于小壳化石内模或内核表面分布,没有纵向穿切的现象(图1(a)~(c)).据此可以鉴定其为钻孔蓝细菌

*Endoconchia lata*的铸模化石^[16~18].(2)成片密集分布的细小坑道和孔洞,截面呈圆形,坑道延伸方向上没有明显粗细变化,直径均匀,约为4 μm.和孔洞交错分布于化石表面,可以见到显著地向内部逐渐深入的现象,转角平缓圆滑(图1(d)和(e)),以及部分坑道的“二歧式”结构(图1(f)).这种形态和分布的特征在相近时代的化石中比较少见,但是可以和以色列白垩纪晚期Mishash组中磷酸钙骨质碎片上的被解释为钻孔真菌的结构对比^[19].此外,现代人骨的腐解实验中,真菌侵蚀也能在磷酸钙基质表面造成类似的密集而均一的孔洞^[20].“二歧式”分支也是钻孔真菌区别于钻孔蓝细菌或钻孔绿藻的重要标志^[21].因此推测其可能是某种营异养生活的真菌留下的钻孔遗迹.大规模成片的生物侵蚀是异养钻孔真菌的一大特征,而富含有机质的磷质基底也是钻孔真菌偏好的环境^[19],向内深入的管道很可能是异养真菌伸向化石内部攫取残余有机质的菌丝造成的.

同时,西乡宽川铺组的AITs一般表现为内壁带有平行纵向纹饰的沟槽孔道,边界清晰,岩石薄片观察显示内部为碳酸钙胶结物填充.其截面一般为矩形或多边形,直径平均在20~40 μm.孔道呈现各种不规则的弯曲和穿插关系,有时会出现尖锐的转角(图1(g)~(i)).上述特征与以往报道类似.此外,研究材料中大量存在的AITs实例还展示了更为丰富的形态特征,例如直径大小变化剧烈(图1(g));纵纹壁饰的排列既有间隔均匀,也有宽窄不均,并且还有不同程度的销蚀(图1(g)和(h));侧壁常发育大角度相交的穿孔等等^[18](图1(g)和(h)).尤其值得注意的是,宽川铺组的AITs样品中还出现了特殊的圆形截面,同时在末端还有球状颗粒(图2(a)和(b))(详细描述分析参见2.2小节).总结以往研究,多边形截面被认为是AITs的典型识别标志之一^[1,22],这一发现丰富了AITs的形态特征,并且能进一步和常具圆形截面的钻孔微生物对比,AITs一般具有纵纹壁饰,分布较为零散和随机,形态呈现明显的不规则性,通过这些依然能够将二者进行区分.

大量观察证明,两种钻孔微生物化石的形态十分稳定,分布也有明显的选择性.然而AITs在大小,截面形状,纹饰和分布方面与钻孔微生物迥然相异,均显示出巨大的不规律性.

(ii) 埋藏保存模式区别. 以上3种微型管状结构表现出显著的保存方式差异,即凸出于化石表面

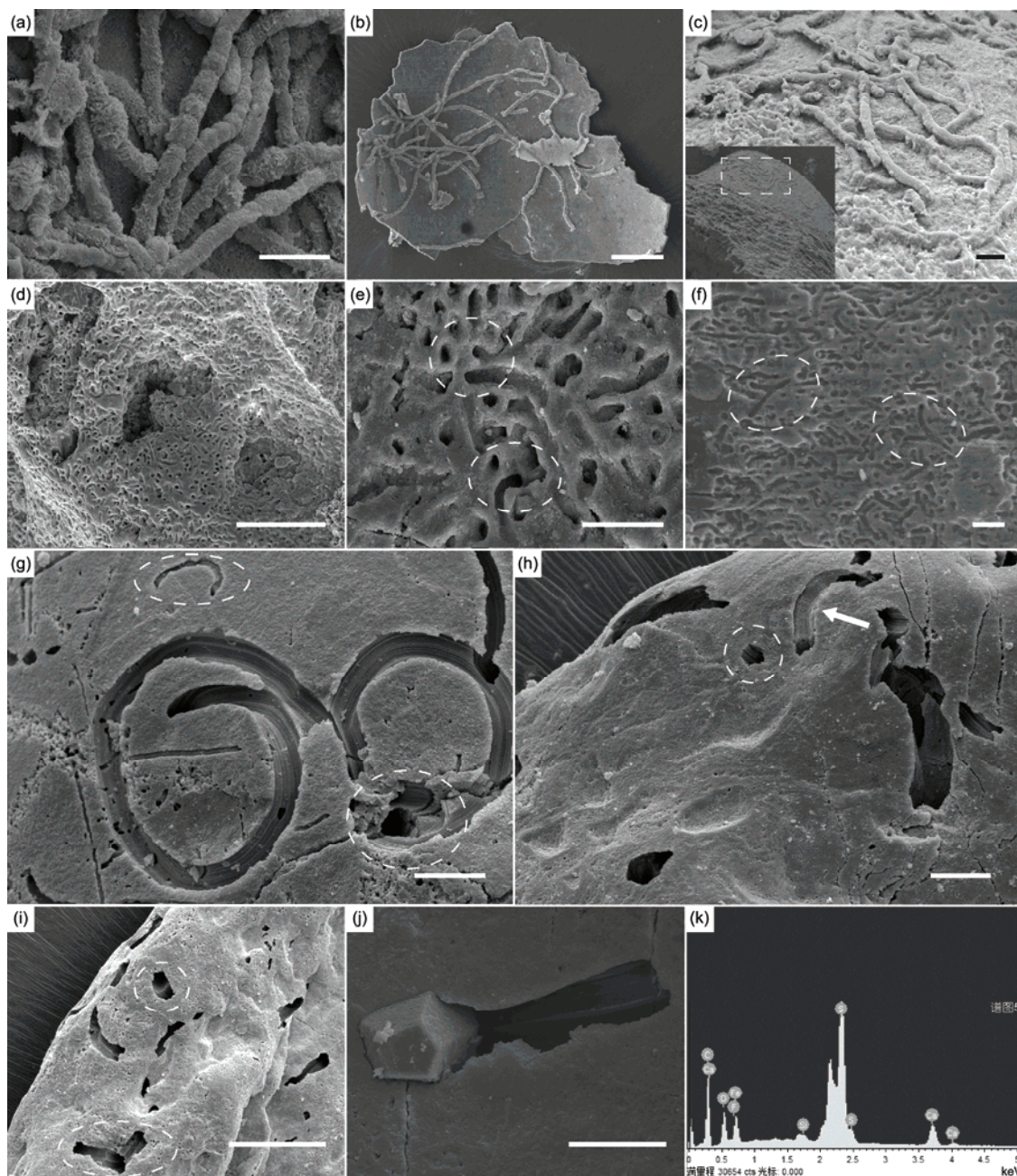


图 1 西乡地区宽川铺组中的微型钻孔结构与异质体拖曳迹(AITs)。 (a) *Endoconchia lata* 钻孔铸模化体细节展示, 显示念珠状结构和互相交叠; (b) 壳体化石残片内凹面的 *E. lata* 钻孔铸模; (c) 马哈螺类化石(*Maikhanella multa*)顶部壳体内模外表面保存的 *E. lata*; (d) 小壳体化石表面密集分布的疑似真菌钻孔遗迹; (e) 钻孔与坑道细节, 注意向内逐渐延伸的坑道; (f) 钻孔坑道的“二歧式”结构; (g) 典型的AITs, 注意其直径差异, 细密而相对规则的纵纹壁饰以及侧壁穿孔; (h) 数条AITs交错穿切的现象以及一个五边形的截面, 箭头所指的AIT管道中部壁饰销蚀, 基本呈现光滑的状态; (i) AITs孔道的尖锐转角和粗细不一的纵纹壁饰; (j) 保存在AITs末端的黄铁矿颗粒, 典型的五角十二面体晶形; (k) (j)中颗粒的能谱图, 显示明显的黄铁矿特征。比例尺: (a), (c), (e), (f), (g), (h), (j)为 20 μm ; (b), (d), (i)为 100 μm

Figure 1 Endolithic microborings and AITs from Kuanchuanpu Formation, Xixiang. (a) Detailed Morphology of *Endoconchia lata* trichomes with moniliform shapes; (b) *E. lata* casts on the concave surface of a small shelly fossil (SSF) fragment; (c) *E. lata* casts on convex surface of *Maikhanella multa* internal mould; (d) dense network of endolith traces as microtunnels and microborings on the surface of SSF; (e) detailed endolith traces, noting the inward-going tunnels; (f) microtunnels with dichotomously branched structures; (g) typical AITs tunnels with relatively evenly arranged longitudinal wall striations and perforations on the side wall, noting the diversified tube diameters; (h) complex conjunctions of multiple AITs and a pentagonal cross section (The arrow shows a relatively smooth wall of one AIT trench with faint wall striations); (i) AITs with polygonal cross sections and sharp turnings; (j) a pyrite terminal propelled grain with pyritohedron shape; (k) EDS spectrum of (j), showing pyrite characteristics. Scale bar: (a), (c), (e), (f), (g), (h), (j) 20 μm ; (b), (d), (i) 100 μm

表 1 西乡地区宽川铺组中的 3 种微型管状结构综合对比

Table 1 Comprehensive comparisons of 3 types of microtubular structures from Kuanchuanpu Formation, Xixiang

结构类型	形态特征	形成阶段	保存方式	直接成因
凸起的丝状体	长条念珠状; 有膨大的圆形末端; 平行化石表面分布	埋藏前的原始钙质壳体, 磷酸盐化尚未开始	磷酸盐铸模化石	钻孔蓝细菌
凹陷的坑道/孔洞	密集成片; 直径均一; 内壁光滑; 有向内部延伸的趋势, 转角圆滑	磷酸盐化后的浅埋藏, 残余有机质主体降解前	钻孔遗迹化石	可能的钻孔真菌
凹陷的沟槽/孔道	形态混杂无规律; 内壁有纵纹; 有尖锐的转角	埋藏加深, 残余有机质进一步降解	孔道本体	异质体拖曳运动

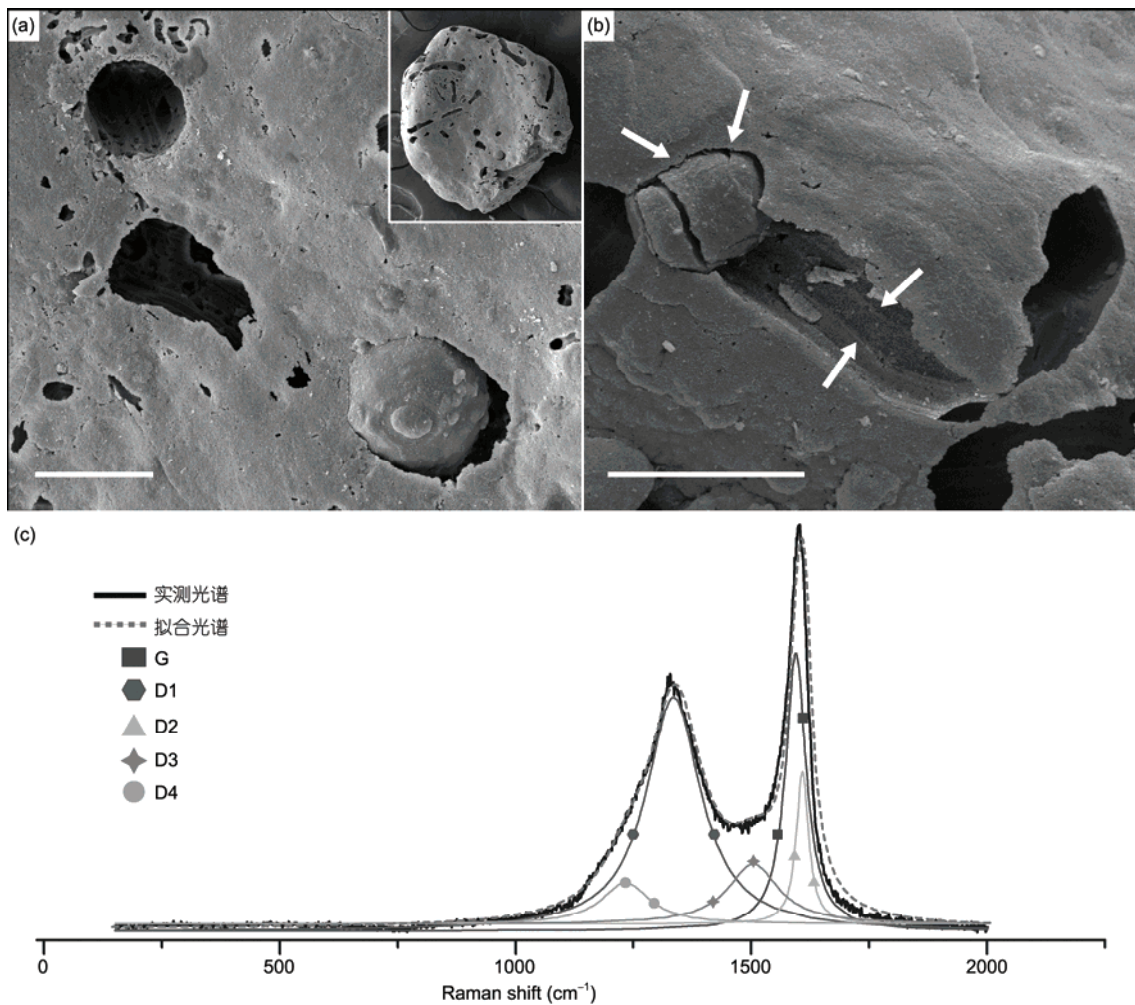


图 2 AITs球状末端颗粒及其拉曼光谱与分峰拟合示例. (a) 带有纵纹壁饰的一个圆形AIT截面以及较为完整的球粒, 显示其轮廓与AITs内缘紧密吻合^[18]; (b) AITs末端的球粒, 其表面凹陷与AITs内壁纵纹相对应(箭头处)^[18]; (c) 另一个未经喷金的碳质球粒(XX-CS-02)的拉曼光谱的分峰拟合示意. 比例尺: (a), (b) 50 μm

Figure 2 Carbonaceous AITs terminal grains and Raman spectrum peak-fitting example. (a) SEM image of one spherical terminal grain, noting the rounded cross-section fits the outlines of the spherules^[18]; (b) SEM image of another spherical terminal grain. The striated wall sculptures of AIT match the profile of the grain (white arrows)^[18]; (c) an illustration of peak-fitting of another uncoated carbonaceous terminal grain (XX-CS-02). Scale bar: (a), (b) 50 μm

的丝状铸模和下凹的钻孔遗迹和拖曳痕迹, 通过埋藏学方面的观察和分析, 认为这主要是由于它们分

别形成于化石埋藏和成岩作用不同阶段.

第一种微生物化石平行小壳化石表面分布的特

征说明其原始状态是位于具钙质壳体的动物原始壳体内部的钻孔,产生于化石埋藏前,甚至可能是与带壳生物共生^[23]。接下来的磷酸盐化作用中,沉积的磷酸钙进入小壳生物原先的体腔形成内模或内核化石,同时这些钻孔也被磷酸盐填筑形成铸模化石。在这一过程中,由于早期成岩作用的弱酸性环境,原始的钙质壳体外侧可能发生不同程度的溶解。一方面,如果在壳体外侧被部分溶蚀,那么替代原始壳体的磷酸盐在沉积过程中将剩余壳体内部的钻孔一并填充,形成保存于内凹面一侧的丝状铸模(图1(b));另一方面,如果溶解发生在壳体内侧或没有溶解,丝状铸模就保存在内模或内核外凸的表面^[24](图1(c))。经过实验室酸蚀处理,最后残存的钙质壳体也被溶解,微生物钻孔的铸模完全暴露出来,并且能够很好地反映微生物的原始形态特征^[18,25]。

第二种微生物化石应在磷酸盐沉积已经基本完成后产生的,使得原始的钻孔得以保留。但是此时含有化石的沉积物还处于较浅的埋藏状态,一方面允许大规模的真菌侵染,另一方面有机质尚能较多地残存,可以促使异养的真菌逐步深入掘进,通过新陈代谢产生酸性物质来溶解磷酸钙^[26]形成钻孔。

AITs产生的阶段,含有化石的沉积物已经开始被更深的埋藏,残余有机质在热力作用下开始降解,产生气体压力^[1],使得附近于之前磷酸盐化作用中形成的黄铁矿晶体和碳质颗粒等异质体的边缘产生压溶现象,并开始沿着压力方向运移形成拖曳痕。AITs在磷酸盐化化石上形成后,又为下一阶段的成岩作用中的方解石胶结物填充。填充物经过醋酸溶蚀后,呈现为现在的状态。

2.2 AITs的碳质末端推进颗粒与化石群经历的埋藏温度

在宽川铺组中磷酸盐化化石上的AITs中,还发现了一些奇异的球状颗粒。笔者之前的研究中,无论是对扫描电子显微镜(scanning electron microscope, SEM)观察样品中的球粒进行EDS(energy dispersive spectrometer)测试,还是对在岩石薄片和未经喷金处理的化石碎片中发现的球粒进行激光拉曼分析,均证明了其主要成分为有机碳质^[18]。AITs与有机碳质物相关的地质记录十分罕见,在19亿年前加拿大Gunflint组硅质岩中,围岩中的有机碳质物可以通过推进颗粒的刮削作用,呈一层压扁的薄膜状积聚在

AITs的末端^[3]。而更直接相关的例子见于27亿年前澳大利亚Maddina组玄武岩里^[27]。填充杏仁孔的玛瑙质中有微细的管道,末端有碳质体保存。这里的碳质体和AITs的尺寸都非常微小(仅3~5 μm),截面均呈现不规则状。因为有机碳能增加石英的溶解度,所以化学溶蚀作用被认为是此AITs形成的主要因素,而有机碳可能来源于玄武岩孔隙未被填充时寄居的微生物群落,或是岩浆体与富含有机物的沉积岩层的相互作用^[27]。但是在我们的材料中,碳质颗粒保存了较大而完整的球体外形,后部未见任何挤压的痕迹。此外,颗粒的边缘与所赋存的AITs管道内缘紧密吻合,其表面的凹陷与AITs管道内壁的纵向纹饰也对应良好(图2(a)和(b)),这说明了是碳质颗粒是相关AITs的直接促成者,而非后期次生聚积而成,并且机械力(气体压力)是主要推进因素^[18]。此外,可以推测是西乡地区的宽川铺组磷酸盐化化石群中较为丰裕的有机质残余为碳质颗粒的形成和较强的气体压力生成提供了可能。近年来的研究表明,沉积岩中碳质物或有机质的石墨化程度与古地温变化有比较密切的关系,这一点通过拉曼光谱反映出来,能够充当地质热事件的记录并且比较敏感的示踪岩体所经历的最高变质温度^[28~32]。由于张家沟剖面化石和围岩均呈灰白色^[12],与其他经典的宽川铺组剖面的岩性相比,缺乏沥青质。因此,研究材料中的碳质末端颗粒的激光拉曼光谱使我们获得了一个推测化石群埋藏之后经历的热变质状况的独特的窗口。这一点除了加深了我们对化石埋藏环境的了解,也能够为日后针对化石中残余有机物的进一步生物地球化学分析提供参考,以更深入地探讨AITs具体形成机制。

研究材料中各个颗粒的拉曼光谱形态基本一致,显示出明显的低变质有机碳特征(图2): (1) 明显的D谱带吸收峰(位于1331 cm⁻¹±)和G谱带吸收峰(位于1600 cm⁻¹±); (2) D峰形态宽缓,强度较低, G峰形态尖锐,强度值较高; (3) D峰左下部略为凸出,可以识别为存在一个隐藏的D4肩峰; (4) 两主峰强度比值(I_G/I_D)约为1.3, 小于1.5。通过拉曼光谱的这些特征,参考当前研究经验,认为其变质温度约在280℃^[33],因此可以选用Lahfid提出的适用于变质温度200~320℃的地质温度计模型进行计算^[34]。首先通过分峰拟合的方式将整个光谱分解为G和D1~D4共5个隐藏峰,分别求得5个峰的面积后使用相应的回归方程,便可计算出两组可用于比对的变质温度值。所得结

果中(表2), 两组温度值吻合度较好, 说明西乡地区宽川铺组的热演化温度峰值为232~261℃, 属于极低级变质作用的范畴。

这样的温度意味着可能将近4 km的埋藏深度^[35]. 虽然还不能完全确定此温度与AITs形成时化石群的埋藏和有机物的热降解状况之间的关系, 但相对较深埋藏造成的高温以及较为坚实的围岩也符合AITs的生成条件^[3,7]. 这一发现为AITs形成所需的热降解温度提供了一个参考和宽泛的上限。

2.3 AITs对特定化石原始成分的指示意义

AITs在化石上的分布一般显示出极大的不规律性, 因为其直接的形成原因是非生物性的, 所以并不与化石种类或生物体组织结构相对应, 基本属于随机生成^[18]. 但研究材料中众多的原牙形刺化石上, AITs却又普遍表现出显著的环绕刺体分布的倾向, 具体表现为: AITs孔道较为严格和连续地沿着刺体表面延伸和转进, 形成单一连续的螺旋状环绕带(图3(a)和(d)), 或由数条分散孔道构成的环带组合(图3(b), (c), (g)); 尤其是在刺体棱角处(图3(e))以及由刺体纵深向表面过渡的位置(图3(i)), AITs都呈现尖锐的转折, 也有部分与刺体表面呈垂直的孔道出现(图3(f)); 大多数外露的AITs孔道都呈现延续性较好的半开放状态, 未出露的孔道也主要分布在刺体外壁中(图3(h)); 这里出现的AITs边缘清晰, 可见绝大多数为多边形或多边形组合状截面(图3(d)~(f)和(i)).

这些现象直接说明了: (1) 孔道的各种尖锐转角以及部分垂向分布, 意味着造成AITs的黄铁矿颗粒是由刺体内部形成并向外推进, 在化石与周围沉积物界面受到明显阻力而急剧改变运行轨迹; (2) 环绕刺体表面的半开放孔道, 反映了推进颗粒受到比较强大的气体压力, 可以支撑其在化石外缘附近连续

环绕并压溶切割磷酸盐基质; (3) 虽未见末端颗粒保存, 但根据截面形状, 可推测其应为自形程度较好的黄铁矿晶体或多个晶体紧密聚合的小团块。

目前的主流观点认为, 原牙形类属于毛颚动物的口器, 原始成分主要为有机质, 如几丁质等, 与真牙形类的生物磷灰石成分不同^[36~38]. 但由于化石保存的关系和直接证据的不甚完备, 对其生物属性和原始成分还存在一定的争议^[39,40]. AITs的分布现象首先可以排除原牙形类的原始成分为坚硬的生物磷灰石, 而非矿化的有机质发生次生磷酸盐化则比较符合形成AITs环绕所需要条件, 即硬度较低, 可能还尚未完全石化的凝胶状基质^[41], 并且充裕的有机质也能在降解过程中提供足够的气体压力, 推动黄铁矿晶体运移, 这也是形成AITs的必要条件. 富含有机物的, 相对缺氧的, 酸性的微环境对黄铁矿形成与磷酸盐化作用都是有利的^[42], 因此二者常常共存. 此外, 在硫酸盐还原细菌的作用下, 较易降解的有机质往往因为快速产生大量H₂S而促成草莓状黄铁矿, 而自形的黄铁矿晶体说明了其生长过程中H₂S供应缓慢而持久, 反映了分解产生H₂S的有机物比较稳定, 对降解作用的耐受力更强^[43], 几丁质相对坚硬而较难降解的特点也符合这一假设. 尽管AITs不是直接生物成因的, 但因其与有机质和微生物活动的密切关系, 有时也能从另一个角度反映部分古生物学的信息, 对保存状况不佳, 缺乏更多识别信息, 但是赋存有AITs的其他化石研究也有一定参考意义。

3 结论

本文综合对比了AITs以及共生的钻孔蓝细菌和钻孔真菌化石在形态、成因和埋藏保存机制的差异, 进一步丰富和明确了它们的区分标准. 并且强调了对于微体化石上疑难结构的识别, 除了静态的形态

表2 西乡地区宽川铺组AITs中碳质颗粒拉曼光谱参数和估算温度^{a)}

Table 2 Raman spectral characteristics and estimated temperatures for the carbonaceous spherules from AIT in Kuanchuanpu Formation, Xixiang

样品编号	G			D1			D2			D3		D4		RA1	RA2	T1 (℃)	T2 (℃)
	位置	半高宽	面积	位置	半高宽	面积	位置	半高宽	面积	位置	面积	位置	面积				
XX-CS-01	1595.7	57.3	197713.6	1337.5	143.3	420842.9	1605.7	32.3	63886.3	1503.8	89643.6	1245.6	49124.4	0.57	1.34	246	237
XX-CS-02	1594.5	53.3	257062.8	1335.2	141.3	558651.4	1608.7	31.4	76816	1504.2	119871.2	1233.4	79238.9	0.58	1.41	261	252
XX-CS-03	1597.2	53.1	324543.9	1332.1	135.1	674509.7	1609.9	32	107392.9	1500.4	91892.2	1235.3	51847.1	0.58	1.39	256	248
XX-CS-04	1591.4	55.6	254488.1	1331.7	131.5	558824.1	1608.4	30.9	114216.8	1495.4	98958.5	1233	55918.3	0.57	1.31	240	232

a) RA1=(D1+D4)/(D1+D2+D3+D4+G); RA2=(D1+D4)/(D2+D3+G); RA1=0.00087+0.3758; RA2=0.00457+0.27^[34]

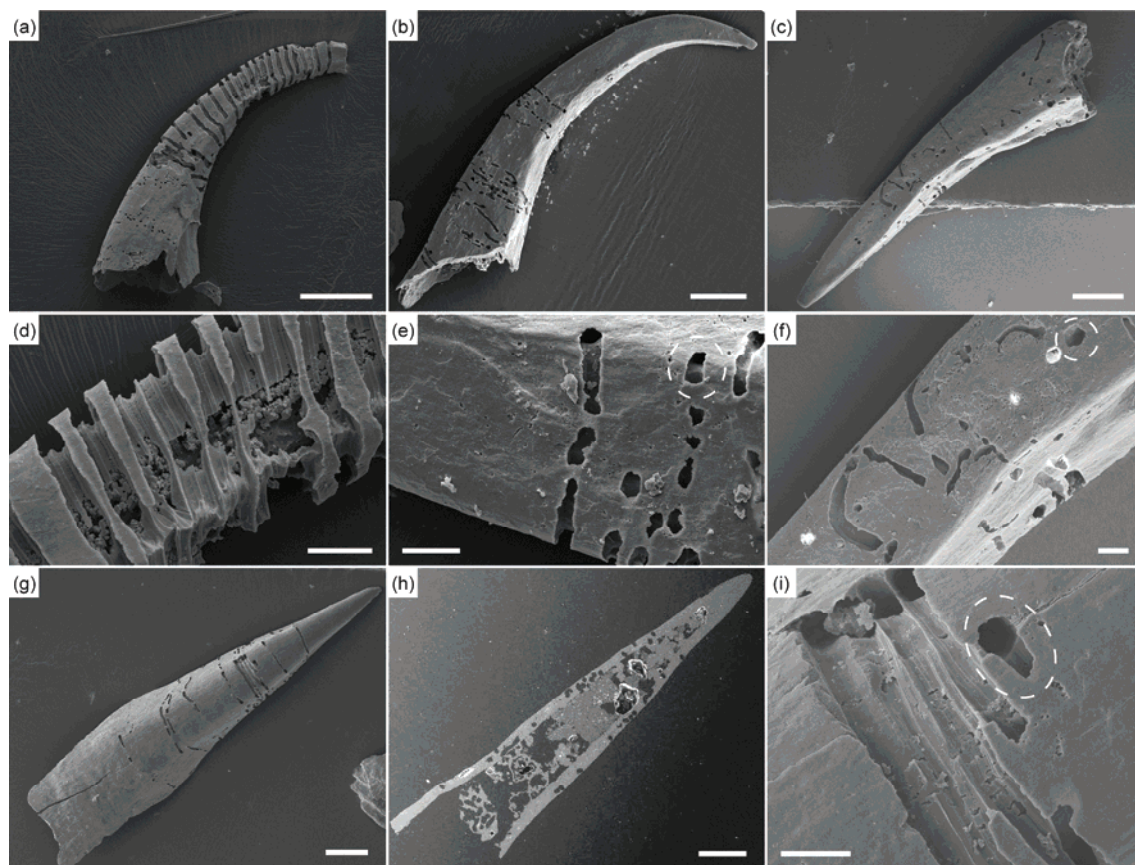


图3 环绕原牙形类刺体分布的AITs. (a), (b), (c), (g) 被AITs环绕的*Protohertzina unguiformis* ((a), (b))和*Protohertzina anabarica* ((c), (g))刺体; (d) (a)中部的放大, 截面形状近似两个组合的多边形; (e) (b)中部的放大, 显示AITs多边形截面和在刺体棱角处急剧的转向; (f) (c)中部的放大, 显示一个规则的五边形截面; (h) (g)中化石的抛光切面, 显示AITs集中分布在刺体外壁; (i) (g)中部的放大, 显示多条环绕AITs在化石和围岩界面附近尖锐的转角和多边形截面. 比例尺: (a), (b), (c), (g), (h) 300 μm ; (d), (e), (f), (i) 50 μm

Figure 3 The AITs that distributed around the protoconodont spines. (a), (b), (c), (g) *Protohertzina unguiformis* ((a), (b)) and *Protohertzina anabarica* ((c), (g)) samples with AITs around the outer surfaces; (d) enlargement of (a), showing cross sections with shape like 2 grouped polygons; (e) enlargement of (b), indicating the polygonal cross sections and sharp turnings at spine aris; (f) enlargement of (c), presenting a well preserved pentagonal cross section; (h) a polished section of (g), noting the AITs mainly occurred within the outer shell of the spine; (i) enlargement of (g), showing polygonal cross sections and sharp turnings of multiple circumferential AITs at the fossil-sediment interface. Scale bar: (a), (b), (c), (g), (h) 300 μm ; (d), (e), (f), (i) 50 μm

学观察, 也应注重考虑动态的埋藏保存因素.

在磷酸盐化石上发现的碳质AITs末端推动颗粒, 证明了在富含有机质参与的磷酸盐化作用中, 黄铁矿晶体并非唯一能造成AITs的异质体, 解释了AITs成因和形态的多样性. 并且通过碳质物的拉曼光谱地质温度计推测出化石群埋藏后经历了极低级变质作用, 变质程度为近变质带, 化石所受影响

较小.

原牙形类化石上赋存的AITs孔道主要由自形黄铁矿晶体拖曳形成, 并呈现明显的环绕刺体分布的特征. 此发现从一个新的角度佐证了原牙形类刺体的原始成分主要是比较坚硬的有机质. 这样的原始成分在通过次生磷酸盐化作用形成化石的过程中, 对黄铁矿晶体的形成和运移都起到了关键作用.

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Summary for “寒武纪早期微体化石上的异质体拖曳迹与微型钻孔结构”

Ambient inclusion trails and microboring structures on Early Cambrian microfossils

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Ambient inclusion trails (AITs) are microtubular structures on various substrates that have occurred widely through the geologic record. They are thought to be generated by the migration of inclusion grains (pyrite, magnetite, carbonaceous spherules), termed “terminal propelled grains”, through a substrate driven by pressure solution from the *in situ* thermal decomposition of organic matter. AITs have been reported frequently from Archean rocks, and also commonly occurring with phosphatized fossils through late Neoproterozoic and Cambrian. During this timeframe, bioturbation was also becoming more intense, and some analogous, AIT-like structures may be more appropriately interpreted as endolithic micro-organisms or borings of predatory animals. It is thus crucial to reduce potential ambiguity between these types of structures, and provide keys for distinguishing AITs and real biogenic structures.

From the Early Cambrian Kuanchuanpu Fm. in Xixiang, Southern Shaanxi, China, numerous microfossils hosting AITs were collected and examined, with recognition of two types of co-occurring micro-borings in addition to AITs. Type 1 micro-boring structures appear as long, unbranched, cylindrical filaments with isodiametric spheroidal expansions on the surface of steinkerns or moulds of small shelly fossils (SSFs); these structures correlate well with casts of known endolithic cyanobacterial fossils, *Endoconchia lata*. Type 2 micro-boring structures are comprised of dense networks of microborings and microtunnels on the phosphatized fossil materials, and are interpreted as trace fossils of endolithic fungi. Such a co-occurrence enables us to make direct comparisons between the variations in microtubular structures. We have made detailed observations of their morphological and taphonomic features, which collectively reveal that they are substantially different in both formation and mechanism of preservation. In the initial stage of formation of Type 1 structures, *E. lata* bored within the original calcite shells of SSFs, with the resulting borings preserved as phosphatic casts during phosphatization. Type 2 structures were caused by infestation of endolithic fungi on the phosphatized fossils while there were still much residual organic materials available for their probably heterotrophic life mode, leaving dense traces of boring behavior. With deeper burial and occurring later in the taphonomic sequence, thermal decomposition of the surrounding organic remains released gases that propelled small inclusions to move through the substrates, forming AIT tunnels.

Some peculiar spherical grains preserved in the distal ends of AITs have been discovered and examined with Laser-Raman and EDS mapping. These data revealed that organic carbon is their major component. The intact spherical profiles without evidence of compression in their tunnel-facing backsides, and the perfect fit of the grain margins and AIT outlines suggest that these carbonaceous grains may have themselves been responsible for AIT formation rather than passive accumulation or secondary filling. Such rare carbonaceous terminal propelled grains of AITs not only explains the morphological diversity (rounded cross sections) of AIT tunnels, but also provide us with a new approach to investigate the taphonomic environment of the fossil-enriched strata. Raman geothermometry of these carbonaceous materials indicates that the Kuanchuanpu Fm. in this area underwent very low-grade metamorphism, with a peak metamorphic temperature estimated at 232–261°C. This implies that the fossils are mostly free from metamorphic overprints, and roughly constrains the upper limits of AIT formation.

In general, as indirectly biogenic structures, the distribution of AITs is random and shows no preference for fossil taxonomy and no particular pattern. However, for those AITs that occurred on protoconodonts, there is an intriguing distribution pattern that AITs traveled around the outskirts of protoconodont spines, forming distinctive spiral grooves. Such a phenomenon may provide auxiliary evidence of their original composition by the following interpretations. The half-open grooves indicate the original composition of protoconodont spines were relatively soft material as opposed to hard bioapatite. The polygonal cross sections suggest, in this case, that the propelled grains were euhedral pyrite crystals, which were usually resulted by the decomposition of more recalcitrant organic materials. Our interpretation is that euhedral pyrite crystals moved from inside of the spines and were trapped by surrounding hard substrate, forming spiral grooves on the fossil-sediment interface. Our observations are consistent with the hypothesis that the original composition of the protoconodont spines are mainly organic, such as chitin, with secondary phosphatization—this hypothesis presents a more favorable scenario for the observed morphologies of the AITs formed by migration of euhedral pyrite crystals through a relatively soft substrate.

ambient inclusion trails (AITs), endolithic micro-organisms, Raman spectrum of carbonaceous material, geothermometer, protoconodonts

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