

豫西寒武系微生物岩中的葛万菌化石及其微观结构*

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摘要 葛万菌(*Girvanella*)是由一个相互串联着的细胞列和外部包绕的多糖质黏性胶鞘组成的蓝细菌化石,是豫西寒武系微生物岩中最常见的钙化微生物。葛万菌丝状体在不同的微生物岩中具有不同的排列方式。潮间带环境中的叠层石其葛万菌主要发育在暗色纹层中,丝状体呈规则的水平状分布。在低能的鲕粒滩滩间或滩后洼地环境中形成的核形石形态及圈层结构均不规则,葛万菌丝状体在其核心和暗色纹层中整体表现为不规则的密集缠绕状;高能鲕粒滩环境中的核形石形态浑圆,圈层结构规则,葛万菌丝状体在核形石暗色纹层中多沿切线方向分布。凝块石形成于台地鲕粒滩滩间局限海环境中,葛万菌丝状体相互交织成不规则团块状发育在凝块中。巨鲕形成于台地鲕粒滩滩间海环境,葛万菌丝状体在内圈层呈密集缠绕状分布,在外圈层则沿切线方向展布。虽然葛万菌群的排列方式在不同微生物岩中有所不同,但是单个葛万菌丝状体的特征相似。在偏光显微镜下,葛万菌丝状体呈略弯曲的无分枝、不分节、细长管状,相互缠绕叠覆;单管由深灰色的管壁(胶鞘)和中间明亮的管芯(细胞列)组成。在电子显微镜下,葛万菌的管壁由直径 $1-2\ \mu\text{m}$ 沿径向放射排列的粒状或短柱状方解石组成,为葛万菌光合作用诱导产生的生物矿物;管芯直径 $10-20\ \mu\text{m}$,长度 $50-200\ \mu\text{m}$ 不等,由圆柱状方解石组成,为成岩期重结晶所致。根据葛万菌的显微结构,结合现代管状蓝细菌的特征,葛万菌由短杆状细胞而非球状细胞组成,其结构应由短杆状细胞组成的细胞列、细胞壁和细胞外的胶鞘(EPS)。

关键词 葛万菌化石 微观结构 微生物岩 寒武系 豫西

1 引言

葛万菌被认为是带有钙化胶鞘的丝状蓝细菌的遗骸(Caron and Jackson, 2006)。它是一个形态属,包含了多种钙化的蓝细菌丝状体(Wray, 1977)。作为一个已经灭绝的属,葛万菌具有以下特点:弯曲,管状,直径相同,有一个钙化的厚壳(胶鞘或胞外聚合物),外径通常 $10-30\ \mu\text{m}$;其丝状体可以单独出现,但大多数情况下相互缠绕形成结。

钙化葛万菌最早出现于中元古代末至新元古代早期,但在之后的新元古代中晚期却很少见及甚至缺失(Turner *et al.*, 2000; Riding, 2006)。这反映出从新元古代冰期到寒武纪之前的地质时期,钙化蓝细菌的地理分布非常有限。钙化蓝细菌的第一次分异与繁盛发生在新元古代与寒武纪之交(Riding and Voronova, 1984)。葛万菌成为寒武纪灰泥(礁、丘)中占统治地位的骨架成分和早古生代碳酸盐岩

灰泥的主要来源(Pratt, 2000, 2001),也见于从奥陶纪到白垩纪的海相灰岩中和现代淡水环境(Klein *et al.*, 1987; Riding, 1991, 2008; Kah and Riding, 2007)。近年来,国内外学者在世界各地的寒武系碳酸盐岩中大量报道了葛万菌化石(郑荣才、曾允孚, 1988; 侯奎、陈延成, 1990; 陈荣坤, 1996; 高建平、朱士兴, 1998; 穆西南等, 2003; 党皓文等, 2008; 郭俊锋等, 2010; 齐永安等, 2013, 2014; 常玉光等, 2014; 代明月等, 2014a, 2014b, 2016; Elicki, 1999; Liu and Zhang, 2012; Chen *et al.*, 2014; Adachi *et al.*, 2014; Han *et al.*, 2015; Zhang *et al.*, 2015)。这反映出葛万菌是寒武系碳酸盐岩中最常见的钙化蓝细菌,也对微生物岩(礁、丘)的形成起到了极其重要的作用。但上述文献对葛万菌的报道多局限在宏观和偏光显微镜下对其描述和分析,在电子显微镜下对其微观结构的阐述则较少。本文通过各种显微手段对豫西寒武系组成微生物岩中的葛万菌化石进行解析,分析宏观形态、微观结构及矿物组成并重建其细

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胞结构。

2 区域地层特征

华北克拉通自新元古代蓟县运动整体抬升以来,长期遭受剥蚀。寒武纪开始海侵,主要表现为稳定的陆表海沉积,其底界超覆于前寒武系不同层位的平行不整合面之上,其顶界为奥陶系马家沟灰岩底部“贾汪页岩”之下的平行不整合面(裴放,1998)。根据古地理及古构造格局、沉积特征、岩性组合、岩相及沉积环境、生物群等综合分析,河南华北型寒武系划分为太行山分区、豫西分区和豫东平原分区,其中豫西分区又进一步划分为澠池-登封小区、灵宝-鲁山小区、叶县-确山小区和卢氏小区(裴放等,2008)(插图 1)。本文研究的葛万菌化石主要采自澠池-登封小区的寒武系第三统馒头组二、三段。该小区寒武系发育较为连续,除底部梅树村阶和筓竹寺阶缺失外,其他阶均有出露。主要包括寒武系第二统辛集组、朱砂洞组、馒头组一段,第三统馒头组

二、三段、张夏组,芙蓉统崮山组、炒米店组和三山子组(插图 2)。其中辛集组、朱砂洞组及馒头组以陆源碎屑岩夹碳酸盐岩沉积为主,而张夏组、崮山组、炒米店组及三山子组则主要发育碳酸盐岩沉积,沉积环境由早期的潮坪相逐渐过渡到晚期的台地滩相。

3 葛万菌化石在微生物岩中的分布

葛万菌丝状体不同的排列(缠绕)方式,构成了不同的微生物岩类型。这种分布的差异性与环境水动力条件的高低具有密切的联系。低能条件有利于葛万菌丝状体的生长与保存,而高能条件下丝状体不太发育。

研究区所发现的叠层石形成于潮间-潮下带上部。由于环境水动力条件较高,葛万菌丝状体主要发育在暗色纹层中,多平行于叠层石纹理方向、呈规则的水平状分布,以减少潮间强水流对其本身的影响,部分丝状体可以直立生长,切穿明亮纹层。

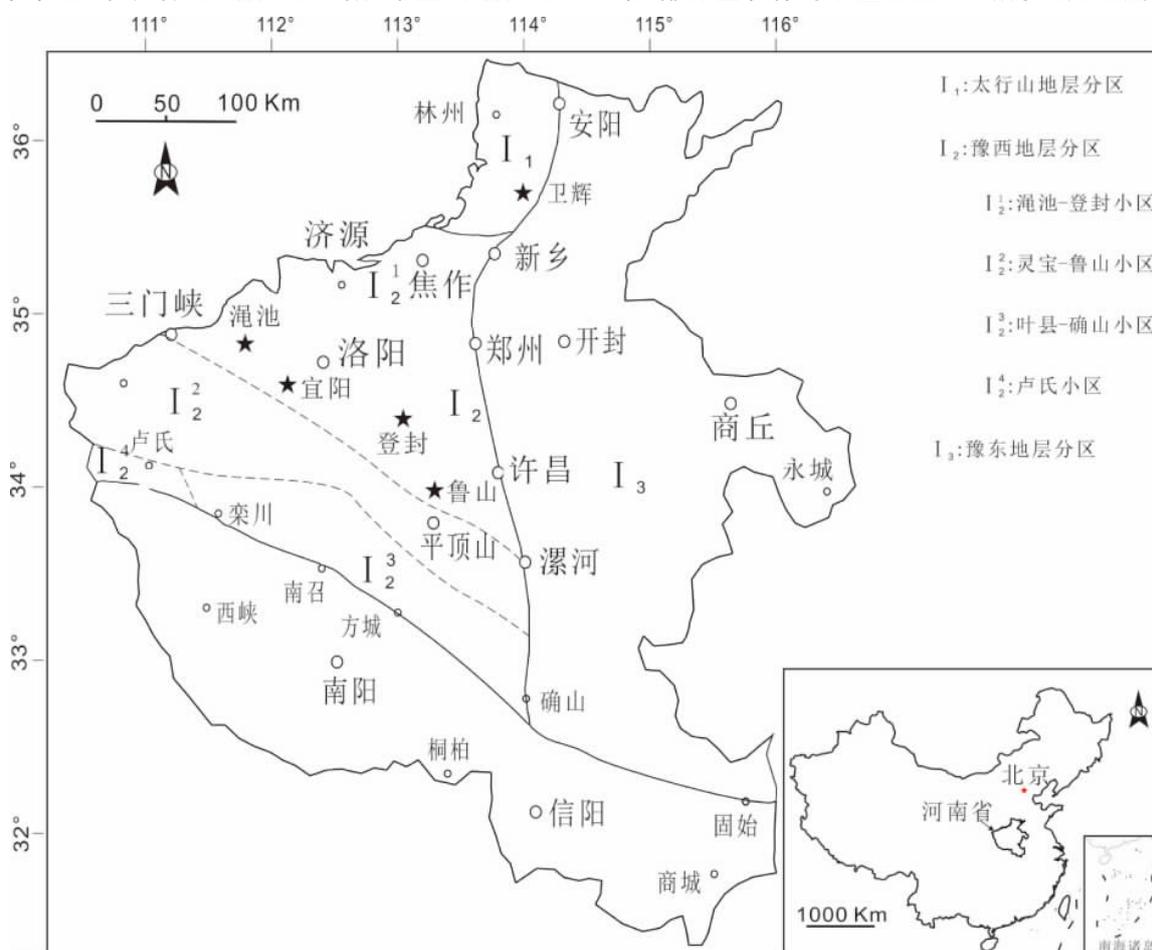


插图 1 河南寒武系分区及剖面位置图(据裴放等,2008 修改)

Map showing the stratigraphic regions and section localities of North China type Cambrian of Henan(modified from Pei et al. ,2008)

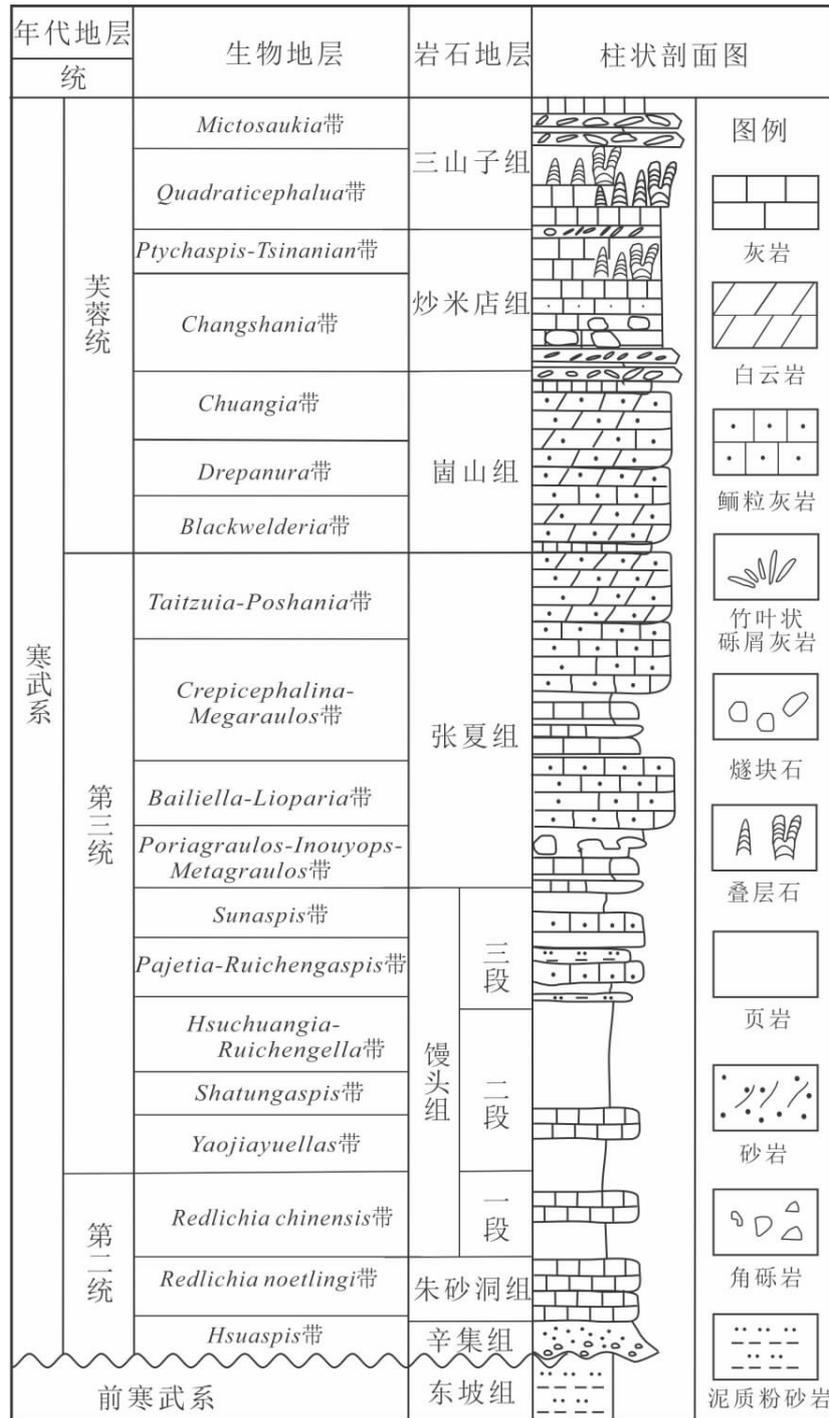


插图 2 豫西寒武纪年代地层、生物地层和岩石地层(据裴放等,2008 修改)

Chronostratigraphy, lithostratigraphy, and biostratigraphy of the Cambrian succession in western Henan(modified from Pei *et al.*, 2008)

核形石的分布在豫西寒武纪不同地区、不同层位有较大的差异。澠池等地馒头组中的核形石形成于高、低交替的滨岸鲕粒滩滩间或滩后低洼地带。由于环境水动力条件总体较低,核形石个体大、形态及圈层结构均不规则,葛万菌丝状体在核形石的核心、暗色纹层甚至核形石之间的围岩中大量发育,整体表现为不规则的密集缠绕、叠覆,在局部生长速度

快的部位,丝状体以穿层和向外突出方式生长,形成的暗色纹层厚而不规则,导致明、暗纹层分界不清;而明亮纹层和最外侧圈层中的葛万菌丝状体则通常沿圈层切线方向分布(齐永安等,2013;代明月等,2016);登封等地馒头组中的核形石形成于潮间-潮下带柱状叠层石的水道间,由于环境水动力条件较高,核形石个体大、形态浑圆、圈层层数多而规则,但

葛万菌丝状体仅在核形石的暗色纹层局部可见(代明月等,2014);豫西各个地区寒武系张夏组所发育的核形石多与鲕粒灰岩伴生,形成于持续高能的地台鲕粒滩环境中,核形石个体较小,形态浑圆,圈层层数少而规则,葛万菌丝状体在核形石暗色纹层中多沿切线方向分布,形成的暗色纹层薄而规则(张喜洋等,2015)。

凝块石在豫西各个地区寒武纪碳酸盐岩中具有相同的特征,均发育在台地鲕粒滩间局限海环境中。在低能条件下,葛万菌丝状体有充足的时间自由生长,留下密集缠绕而且无定向的丝状体集群,形成了凝块石灰岩中丝状体凝块的不规则形态(齐永安等,2014)。

研究区发现的巨鲕主要见于渑池、宜阳等地的张夏组下部,形成于高、低能交替、以高能为主的台地鲕粒滩间海环境。葛万菌丝状体在巨鲕圈层的

分布包括 3 类:紧靠核心的丝状体略稀疏,一端依附核心向外生长,并与其他丝状体相互连接形成网格状;内圈层的丝状体大致沿圈层切线方向匍匐排列;外圈层的丝状体则密集缠绕、叠覆;巨鲕边缘分布的丝状体与圈层中的相比颜色更深,排列致密、杂乱(代明月等,2014)。

4 葛万菌化石的偏光显微镜特征

作者通过大量磨制豫西寒武系馒头组碳酸盐岩薄片,在不同类型的微生物岩中发现了大量的葛万菌化石。插图 3A—D 分别展示了巨鲕外圈层、核形石圈层、叠层石纹层和凝块石凝块中的葛万菌群。虽然葛万菌群的排列方式在不同微生物岩中有所不同,但是单个葛万菌丝状体的特征相似。下文以核形石中的葛万菌化石为例介绍其微观结构特征。

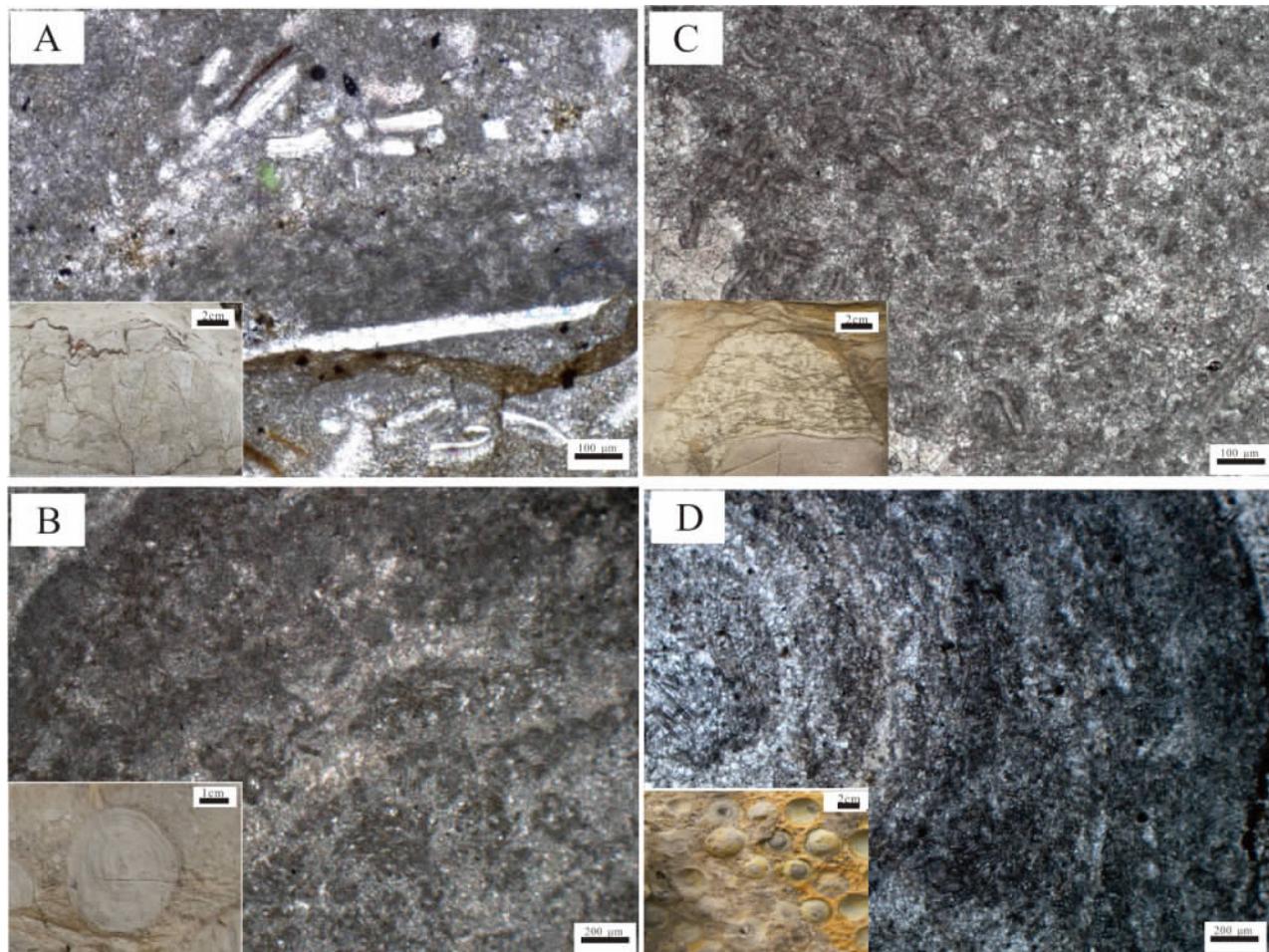


插图 3 不同微生物岩中葛万菌的偏光显微照片

Photos showing *Girvanella* in different microbialites under polarizing microscope

葛万菌丝状体分别取自 4 种微生物岩:A. 巨鲕外圈层,B. 核形石圈层,C. 叠层石纹层,D. 凝块石凝块。

Girvanella filaments in four kinds of microbialites:A. the outside cortex of giant ooid,B. the cortex of oncoid,C. the lamination of stromatolite,D. the clot of thrombolite.

在偏光显微镜下,葛万菌丝状体单管弯曲,不分叉,直径均匀,由深灰色的管壁和中间明亮的管芯组成。在所有微生物岩中,葛万菌的周围是颜色较深的灰泥或泥晶颗粒(插图 3),这些灰泥或泥晶颗粒是葛万菌死亡后腐烂降解的产物。插图 3 中的微亮晶方解石为葛万菌腐烂降解形成的灰泥在后期成岩作用影响下重结晶所致。个体稍大且集中分布的亮晶方解石(插图 3A,C)为微生物黏结捕获沉积物中的亮晶方解石颗粒在后期成岩作用影响下重结晶所致,小颗粒在压力和温度的影响下逐渐溶解,促使晶粒合并,逐渐长大;这些大颗粒亮晶方解石个体较为明亮干净,并且常孤立地保存在微晶颗粒之间,称作“亮晶补丁”。个体稍小的亮晶方解石(插图 3C、D)为微生物黏结捕获沉积物中的亮晶方解石颗粒,其颗粒边界较为模糊,且颜色偏深,常成片分散出现。

5 葛万菌化石的电子显微镜特征及能谱分析

对于偏光显微镜观察到葛万菌的标本,取其自然裂开面,用 5%醋酸淋洗 10 秒,烘干,喷金置于电子显微镜下观察,可观察到化石清晰的空间结构和矿物形态。在 400、500 倍放大倍数下就可以见到其管状延伸形态(插图 4A,B),与透射偏光镜下观察到的无异,丝状体弯曲,相互缠绕,部分丝状体延伸方向具有一定的定向性。当放大到 2 000 倍时,葛万菌丝状体相互缠绕、叠覆形态更加清晰可见(插图 4C,D)。化石的纵切面和横切面都有出现,说明葛万菌呈三维空间分布。组成丝状体的矿物颗粒可明显分为三类:密集分布的小颗粒(插图 4A,虚线)、单个出现的大颗粒(插图 4A,实线)以及成片出现的中等大小的颗粒(插图 4B,虚线),结合透射偏光显微镜下观察到的两类方解石的特征,则小颗粒矿物即为蓝细菌降解形成的灰泥,大颗粒矿物为微生物席捕获的亮晶方解石,而成片出现的中等颗粒则为灰泥发生重结晶作用而形成的微亮晶方解石。

在高倍镜下,葛万菌丝状体清晰地呈现出管芯矿物和管壁矿物。管芯矿物由长柱状微亮晶—亮晶方解石组成,直径 10—20 μm ,延伸长度 50—200 μm ,应为葛万菌的细胞列。部分长柱状方解石常沿横向裂解成许多短柱,短柱的长短不一,长度 5—100 μm 不等,有时甚至破碎成小颗粒(插图 4C,D)。管壁矿物为微晶方解石,应为细胞外的胶鞘,呈短柱状或近似等粒状围绕放射状管芯(细胞

列)分布,矿物颗粒长 1—2 μm ,直径 0.5—1 μm ,在管芯两侧垂直于管芯长轴向外生长,在管芯两端,沿着管芯长轴方向生长(插图 4E—H)。

葛万菌丝状体的管状横切面清晰地反映出同心环结构(插图 5)。管壁(胶鞘)为紧密围绕着管芯(细胞列)放射状排列的短柱体矿物。部分管芯矿物因成岩作用碎裂成直径 5—7 μm 的放射状小颗粒(插图 5A,B)。这种放射性的碎裂特征与文石的性质相吻合。有些管芯矿物仍保留有完整的圆柱形矿物形态(插图 5C)。在管芯和管壁矿物之间存在纳米级的空隙,表明管芯(细胞列)和管壁(胶鞘)两种矿物之间可能存在细胞壁结构(插图 5D,E)。

对管芯长柱状矿物的放大可以看出,其表面并非光滑平整,而是呈现为粗糙凹凸的形态(插图 6A)。长柱状矿物表面发育一个个凹坑,其大小与管壁矿物相当,可以推断这些凹坑是管壁矿物在管芯矿物表面的嵌坑(插图 6B)。管芯晶体上的片状和螺旋状生长纹表明晶体以螺旋状和层状生长方式晶出(插图 6C,D)。从插图 6E、F 展示的管壁与管芯矿物间的接触关系来看,管壁与管芯并非紧密接触,之间有纳米级的空隙。插图 6G 为管壁矿物细节图,可见矿物的层状生长纹,最外层晶面可见瘤状突起。根据晶体的层生长理论,这些突起就是在下层平整的面网上新生的质点,来提供三面凹角和二面凹角,供本层面网的生长。插图 6H 显示管壁矿物上的一些针状矿物。

据上面的描述,在视野中共识别出三种不同形态的矿物类型:1)组成管芯的长柱状矿物,2)组成管壁的放射状排列的短柱状矿物,3)葛万菌菌体之间片状或颗粒状的矿物。背散射图像显示的管芯、管壁和外圈充填的矿物颜色一致,表明它们在成分上无差别(插图 7,虚线圈定的矿物在背散射图片中颜色略深,表面相对光滑,能谱分析为硅铝矿物或二氧化硅,为蓝细菌席捕获粘结的碎屑物质,不计入上述统计范围)。横纵切面上依次对管芯、管壁和围岩中三种类型的矿物进行能谱的点分析(插图 8,9)结果表明,这些矿物均为纯碳酸钙,且 Ca、O、C 三种元素的比例没有明显的差异。插图 10 面扫描显示的结果也均为碳酸钙(除捕获的碎屑或粘土矿物)。由于管壁矿物较松散,易脱落,接收能量较周围部位低,所以在图像中管壁位置出现一个相对较暗的黑圈。由于受制于微区取样技术的限制,仅能对全岩进行 XRD 分析。我们将化石含量相对较高的区域磨制成 200 目粉末进行测试,测试结果显示的峰值与方

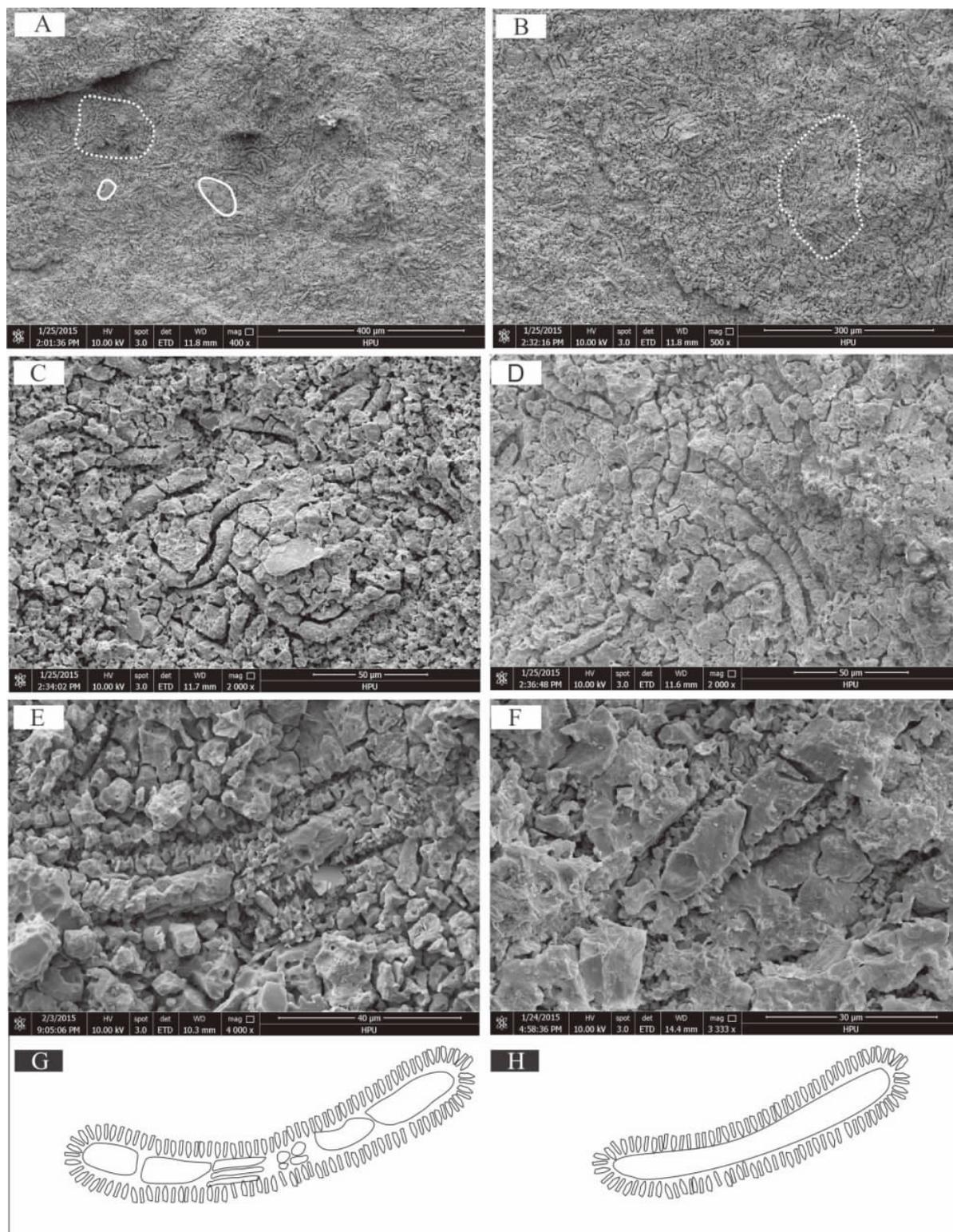


插图 4 核形石中的葛万菌丝状体及在纵切面下的超微结构特征

Photos showing *Girvanella* filaments and their ultrastructural features of longitudinal section in oncoid

A—D. 不同放大倍数下均可见到葛万菌丝状体相互缠绕叠覆在一起；A 虚线圈定的小颗粒为葛万菌降解形成的灰泥，实线圈定的大颗粒为葛万菌捕获的亮晶方解石；B. 虚线圈定的颗粒为灰泥重结晶作用形成的微亮晶方解石。E—H. 葛万菌丝状体中管芯与管壁矿物的分布状态。A—D. *Girvanella* filaments were intertwined with each other under different magnifications; The small grains marked in dash line in fig. A are the marl degraded by *Girvanella*. The big grains marked in solid lines in fig. A are the microspar calcites transformed from marl by recrystallization. The grains marked in dash line in fig. B are the marl degraded by *Girvanella*. E—H. The mineral distribution in tube core and tube wall of *Girvanella* filaments.

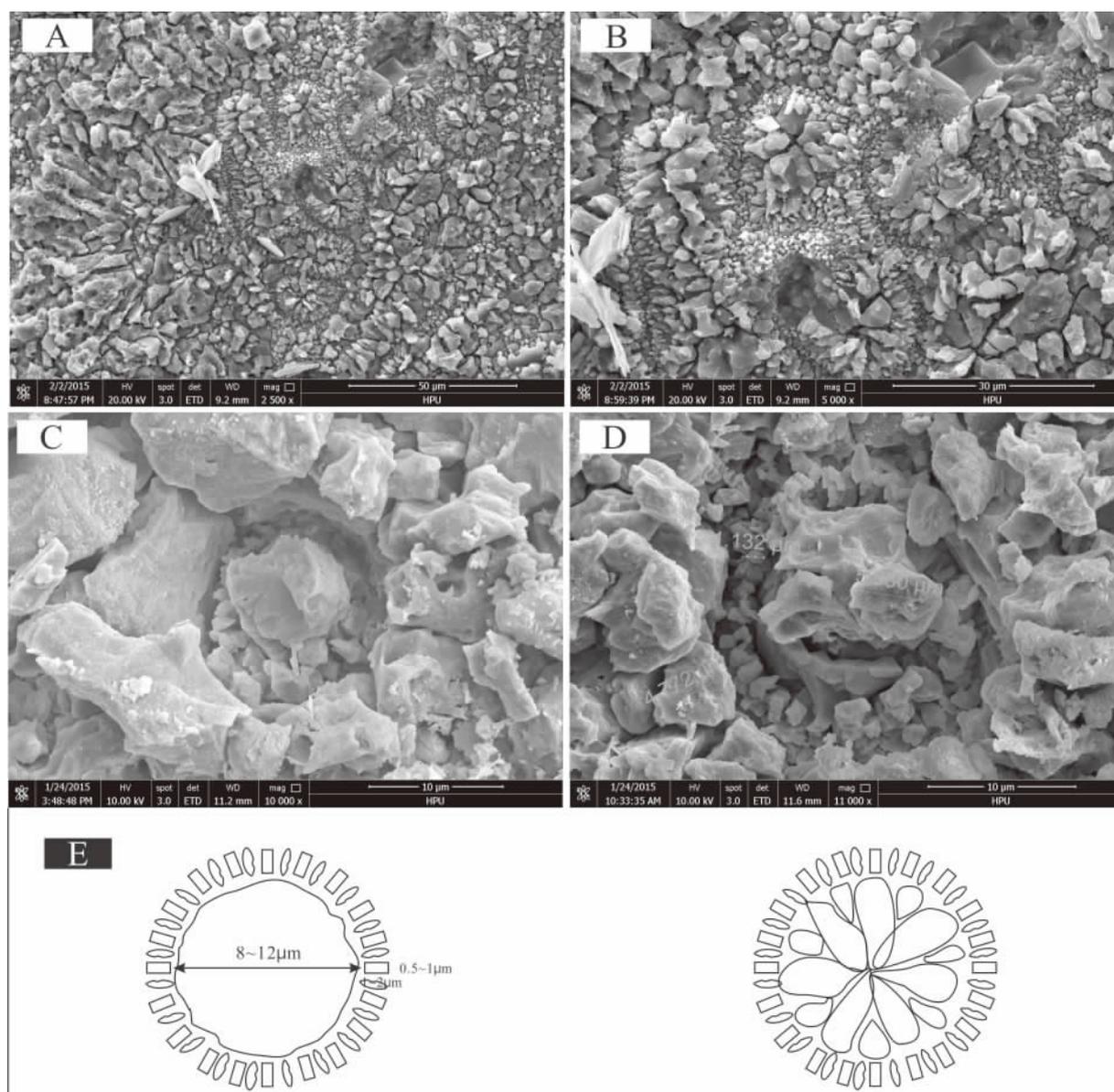


插图5 核形石中葛万菌丝状体横切面的超微结构特征

Photos showing the ultrastructural features of transverse section of *Girvanella* filaments in oncid

A—B. 低倍镜下葛万菌丝状体的横切面特征; C—E. 高倍镜下葛万菌丝状体中管芯与管壁矿物的分布状态。

A-B. The transverse features of *Girvanella* filaments at low magnification; C-E. The mineral distribution in tube core and tube wall of *Girvanella* filaments at high magnification.

解石峰值严格对应,并没有其他孤峰,因此三种矿物均为方解石(插图11)。

6 葛万菌丝状体细胞结构重建

与相似蓝细菌的对比可以加深对葛万菌化石形态的认识。常产于现代包气带环境的 *Scytonema julianum* 在形态上与葛万菌最为相近。*Scytonema julianum* 是一种常见的嗜气性蓝细菌,生活在热带温湿气候,在土壤、岩石、树枝和洞穴壁上(Jones

and Peng, 2014)。这种丝状蓝细菌相互缠绕,直径4—11 μm ,外面包裹着发育完好的钙化胶鞘,总直径可达11—25 μm ,胶鞘由四种不同形态的方解石矿物组成,包括无定形碳酸钙、针状方解石晶体、三射状方解石晶体和树枝状方解石晶体。这些矿物均在细菌活着时产于细胞的胶鞘中。

葛万菌化石在形态和直径上与 *Scytonema julianum* 相似。不同点是:①葛万菌胶鞘仅由一种短柱状放射排列的方解石组成,结构较为简单,这也符合生命结构由简单到复杂的进化规律,这种进步

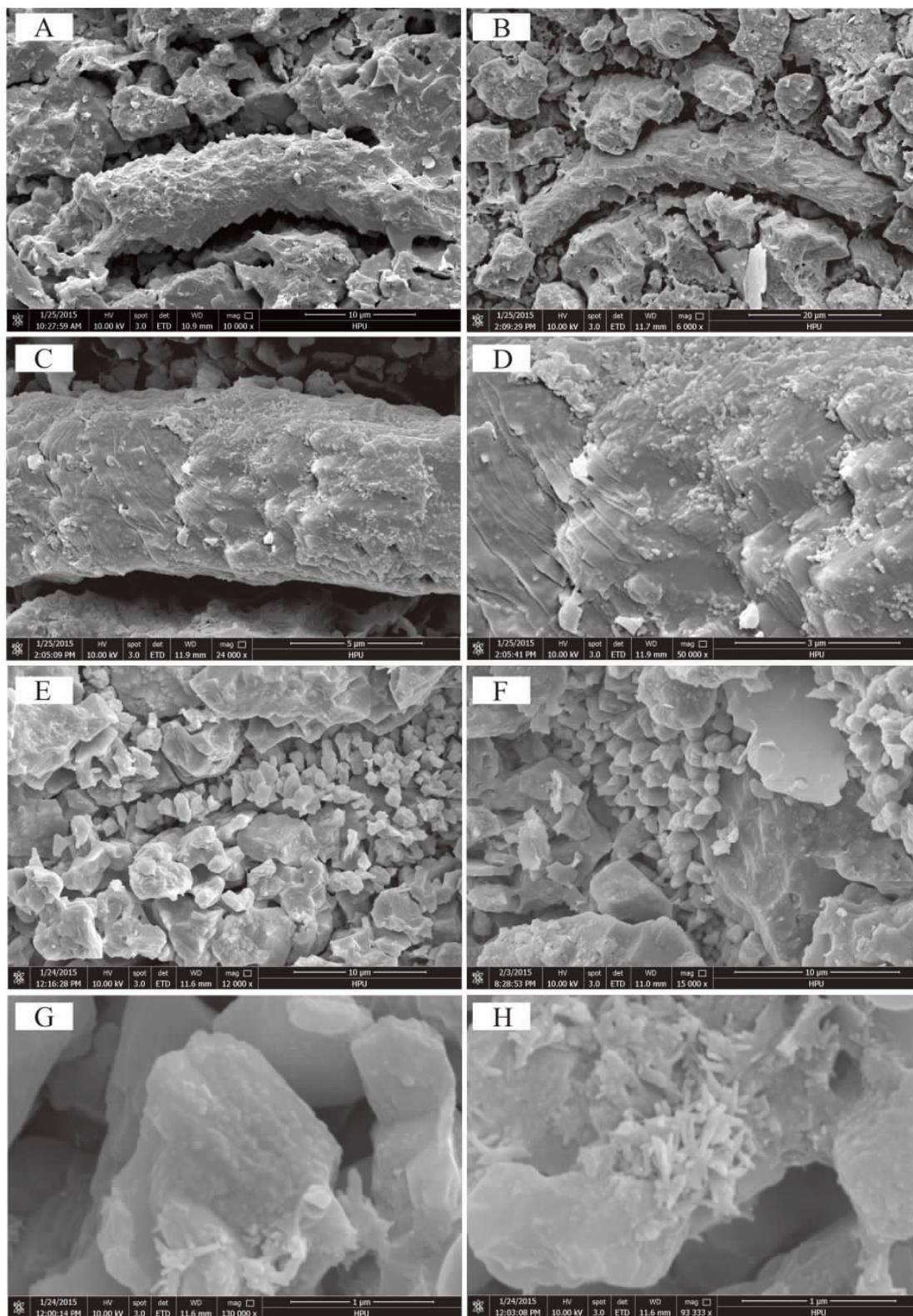


插图 6 核形石中葛万菌丝状体管芯、管壁矿物的超微结构特征

The ultrastructural features of minerals in tube core and tube wall of *Girvanella* filaments in oncooid

A—B. 管芯矿物表面粗糙凹凸的形态, C—D. 管芯矿物表面的螺纹状生长纹, E—F. 管芯表面附着的长柱状管壁矿物, G—H. 管壁矿物表面的瘤状突起和附着的针状矿物。

A-B. The bumpy shape on the surface of tube core mineral, C-D. the threaded growth patterns on the surface of tube core mineral, E-F. the long cylindrical minerals of tube wall minerals on the surface of tube core mineral, G-H. the protuberances and needle-like minerals on the surface of tube wall minerals.

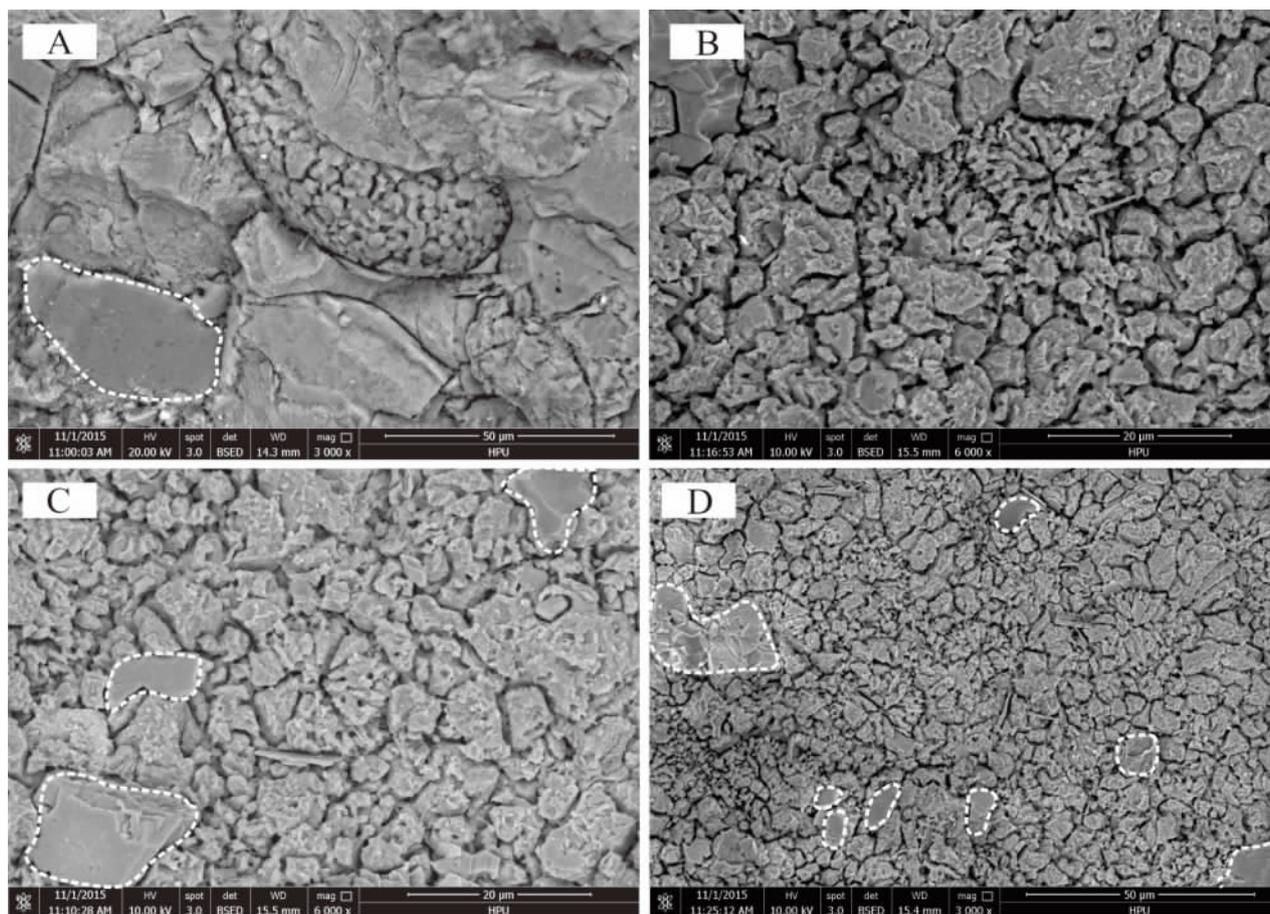


插图 7 核形石中葛万菌丝状体及其围岩的扫描电子显微镜背散射图片

BSED photos showing the ultrastructural features in *Girvanella* filaments and surroundings in oncoid

图中虚线圈定的矿物为硅铝矿物或二氧化硅,是葛万菌席捕获粘结的碎屑物质。

The minerals marked in dash lines are silica-alumina minerals or silicon dioxide, which are the grains trapped by *Girvanella*.

性就体现在胞外聚合物成分和结构上的复杂化。②葛万菌在胶鞘内侧未发现细胞壁,仅有纳米级的空隙,有可能是随成岩时间的增加,细胞壁降解消失的缘故。③葛万菌管芯(细胞列)中有长柱状方解石,而 *Scytonema julianum* 则呈现空心结构。葛万菌为古生代特有的蓝细菌种类,经历多次成岩作用的改造,其管芯已经成岩重结晶作用充填有矿物。而 *Scytonema julianum* 可能还未经历饱和溶液的充填阶段,因此在管芯内没有晶体的生长。

Scytonema julianum 形态的分析对葛万菌丝状体的重建具有重要的启示意义。结合现代丝状蓝细菌的结构特征,葛万菌丝状体的结构应为细胞列组成的丝状体、细胞壁和细胞外的黏性胶鞘(插图 12)。插图 6 中管芯方解石连续生长的晶纹特征表明晶体生长时管内空间应该是一个连续没有断开的环境,这可以解释为细胞列在完全降解后被碳酸钙饱和溶液充填,生长为长柱状晶体,而其上的凹坑则很可能是压实作用使得管壁矿物嵌入管芯内部。

由于缺乏确凿的证据,对于葛万菌的细胞内部结构了解甚少,但遵从现实主义原则,结合 *Girvanella* 直径等大的特征,葛万菌应由短杆状细胞而非球状细胞组成。

7 结 论

(1)葛万菌化石保存在豫西寒武纪巨鲕、核形石、叠层石和凝块石等微生物岩中。这种分布的差异性与环境水动力条件的高低具有密切的联系。葛万菌丝状体在不同的微生物岩中具有不同的排列(缠绕)方式。叠层石形成于高能的潮间-潮下带上部,其中的葛万菌主要发育在暗色纹层中,丝状体呈薄而规则的水平状分布。高能条件下形成的核形石形态浑圆、圈层结构规则,但葛万菌丝状体仅在核形石的暗色纹层局部可见;低能条件下形成的核形石形态及圈层结构均不规则,葛万菌丝状体在核心和暗色纹层中整体表现为不规则的密集缠绕、叠覆状。

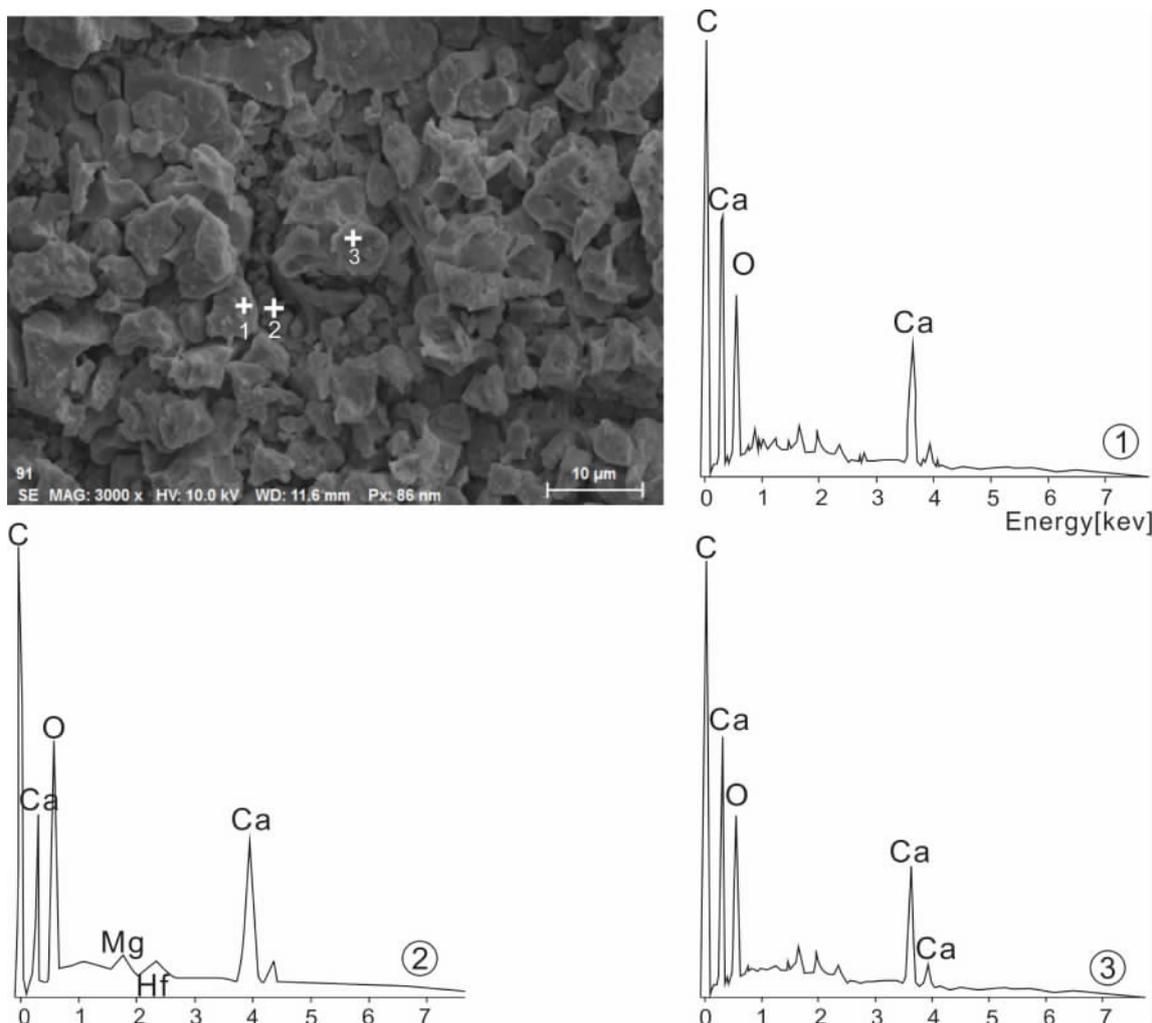


插图 8 横切面下 EDS 数据显示核形石中葛万菌管芯、管壁和围岩矿物均为 CaCO_3
 Similar chemical component (CaCO_3) among tube core, tube wall and surroundings indicated
 by EDS in the transverse section of *Girvanella* in oncolid

1. 围岩矿物, 2. 管壁矿物, 3. 管芯矿物。

1. Minerals in surroundings of *Girvanella* filament, 2. minerals in tube wall of *Girvanella* filament, 3. minerals in tube core of *Girvanella* filament.

凝块石发育在低能的台地鲕粒滩滩间局限海环境, 其中的葛万菌丝状体相互交织成不规则团块状发育在凝块中。巨鲕形成于高、低能交替、以高能为主的台地鲕粒滩滩间海环境, 葛万菌丝状体在内圈层呈密集缠绕状分布, 在外圈层则沿切线方向展布。

(2) 虽然葛万菌群的排列方式在不同微生物岩中有所不同, 但是单个葛万菌丝状体的特征相似。偏光显微镜下, 葛万菌丝状体单管弯曲, 不分叉, 直径均匀, 由深灰色的管壁(胶鞘)和中间明亮的管芯(细胞列)组成。电子显微镜下, 葛万菌化石纵切面呈现丝状体相互缠绕、叠覆的形态, 横切面清晰地反映出同心环结构。管芯(细胞列)矿物由长柱状微亮晶—亮晶方解石组成, 直径 10—20 μm , 延伸长度 50—200 μm 。部分长柱状方解石常沿横向裂解成

许多短柱, 短柱的长短不一, 长度 5—100 μm 不等, 有时甚至破碎成小颗粒。管壁(胶鞘)矿物由径向放射排列的微晶方解石组成, 呈短柱状或近似等粒状围绕管芯分布, 矿物颗粒长 1—2 μm , 直径 0.5—1 μm , 在管芯两侧垂直于管芯长轴向外生长, 在管芯两端, 沿着管芯长轴方向生长。

(3) 结合现代丝状蓝细菌的结构特征, 葛万菌由短杆状细胞而非球状细胞组成。其结构应为细胞列组成的丝状体、细胞壁和细胞外的黏性胶鞘。组成细胞列(管芯)的方解石则是在葛万菌死亡降解后, 海水进入空腔的细胞列中, 成岩重结晶作用所致; 在葛万菌化石的细胞列(管芯)与胶鞘(管壁)间发育有纳米级的空隙, 可能是细胞壁降解消失的缘故; 组成胶鞘(管壁)的方解石为葛万菌生命活动时期光合作用诱导产生。

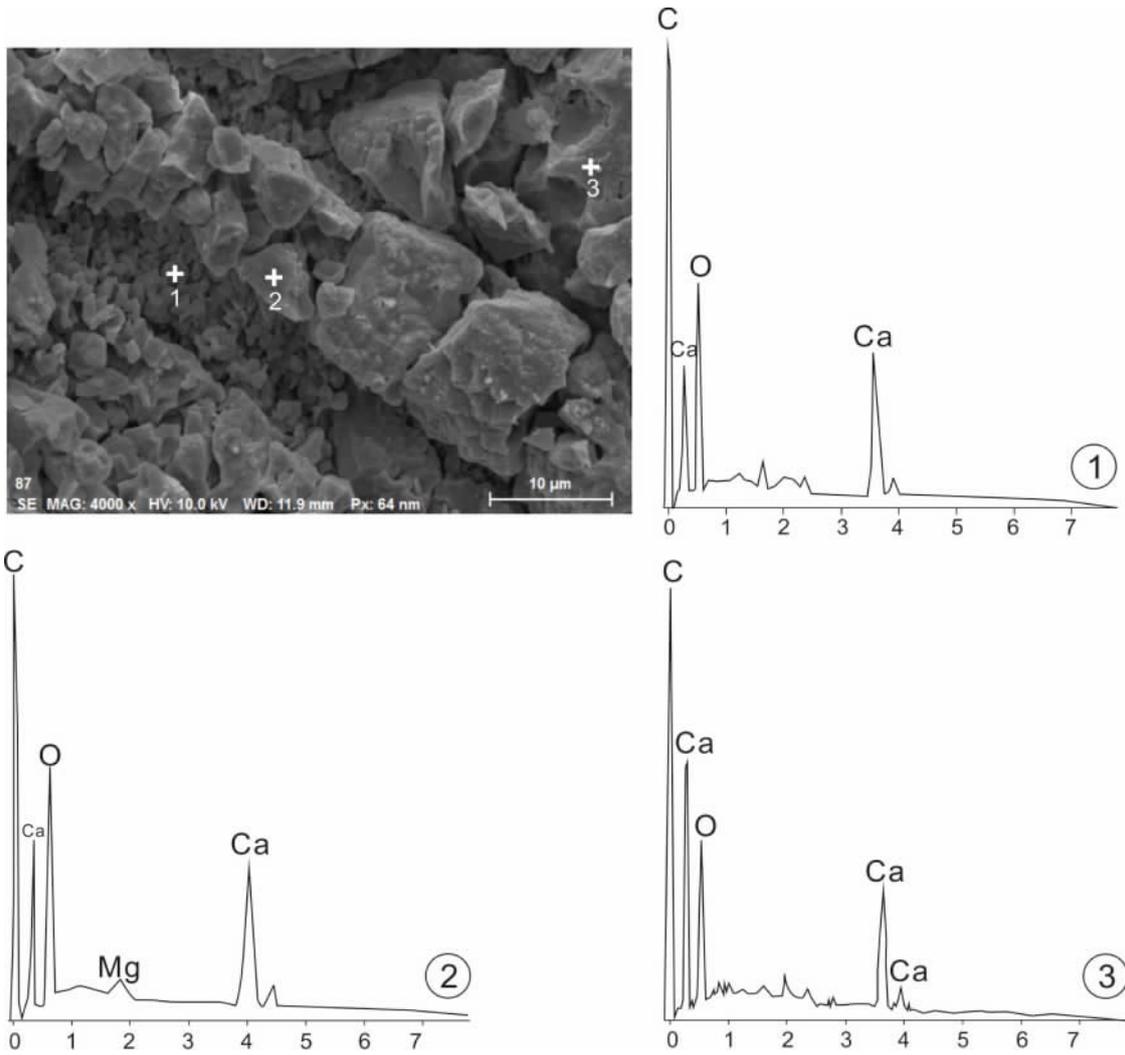


插图 9 纵切面下 EDS 数据显示核形石中葛万菌管芯、管壁和围岩矿物均为 CaCO_3
 Similar chemical component (CaCO_3) among tube core, tube wall and surroundings
 indicated by EDS in the longitudinal section of *Girvanella* in oncoid

- 1. 管壁矿物, 2. 管芯矿物, 3. 围岩矿物。
- 1. Minerals in tube wall of *Girvanella* filament, 2. minerals in tube core of *Girvanella* filament, 3. minerals in surroundings of *Girvanella* filament.

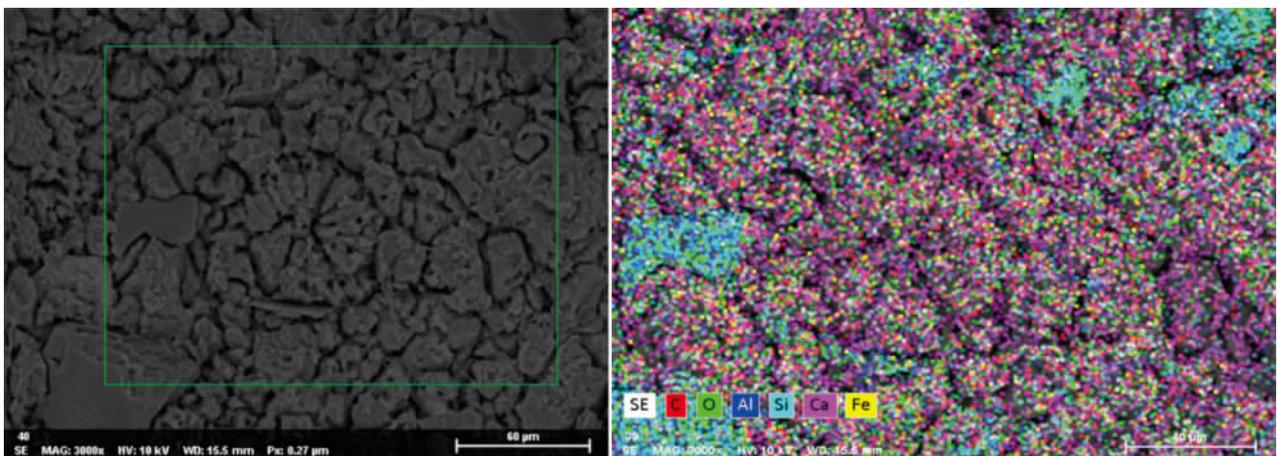


插图 10 核形石中葛万菌横剖面下 EDS 面扫描图像
 Area scan mode of EDS showing the similar chemical component (CaCO_3) among tube core,
 tube wall in *Girvanella* and surrounding fillings of oncoid

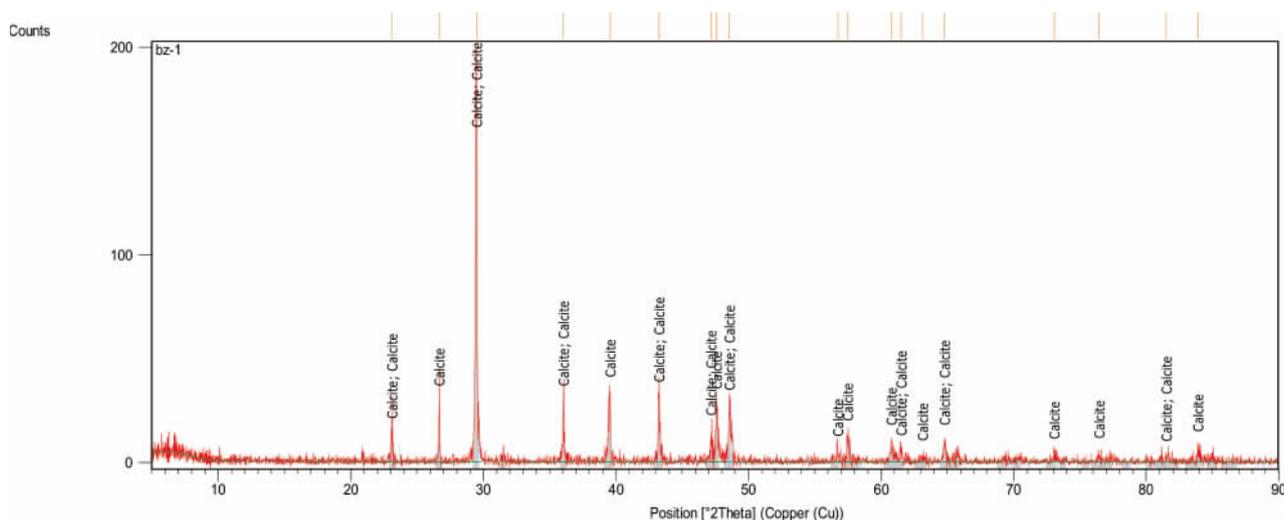


插图 11 核形石中葛万菌丝状体及其周围的碳酸盐矿物的全岩 XRD 数据

The total rock XRD data of carbonate minerals in *Girvanella* filaments and their surroundings of oncoïd



插图 12 葛万菌丝状体结构重建

The structural reconstruction of *Girvanella* filaments

致谢 感谢审稿专家们提出的有益建议和修改意见。

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GIRVANELLA FOSSILS AND THEIR MICROSTRUCTURE FROM CAMBRIAN MICROBIALITES OF WESTERN HENAN

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Key words *Girvanella* fossils, microstructure, microbialites, Cambrian, western Henan

Abstract

Girvanella is a kind of cyanobacterial fossil with interconnected cell row and enveloping polysaccharide mucilaginous sheaths and is the most common calcified microbes in Cambrian microbialites of western Henan. *Girvanella* filaments display different distributions in different microbialites. The filaments in stromatolite of intertidal flat environment mainly occur in dark laminations and display as a regular horizontal distribution. The oncoids in low-energy coastal oolitic inter-shoal or back-shoal environments are dominated by irregular shape and cortex structures. *Girvanella* filaments are mainly irregular densely winding in nuclei and dark cortex of the oncoids. The oncoids in high-energy oolitic shoal environments have a round shape and regular cortex structures in which *Girvanella* filaments are distributed in the dark cortex of the oncoids along the tangent direction. The thrombolites were formed in oolitic inter-shoal of restricted platform environments in which *Girvanella* filaments are mainly densely winding, being intertwined with each other with irregular distribution in the clots.

The giant ooids were preserved in oolitic shoal of open platform environments in which *Girvanella* filaments appear as densely winding in inner cortex and as the tangent direction in the outer cortex. Each individual tube of *Girvanella* filament display similar features although *Girvanella* filaments have the different distributions in different microbialites. Each individual tube consists of a dark grey tube wall (sheath) and bright tube core (cell row) under polarizing microscope. Viewed under electronic microscopy, the tube wall of *Girvanella* consists of radial-arrayed granular or short columnar calcites which have a diameter of 1-2 μm and are considered to be biominerals induced by photosynthesis of *Girvanella*. The tube core is made up of cylindrical calcites with the diameter of 10-20 μm and the variation length of 50-200 μm , which are the products of recrystallization during diagenesis. According to the microstructure of *Girvanella* in combination to the features of modern tubular cyanobacteria, *Girvanella* is made up of short rod cells instead of coccoid cells. Its microstructure includes strands of short rod cells attached end-to-end, cell walls and extracellular sheaths (EPS).