鲕粒滩相灰岩特别的核形石灰岩帽

——以山西繁峙茶坊子剖面寒武系张夏组为例

梅冥相[1,2)], MUHAMMAD Riaz[1)], 孟庆芬[1)], 刘丽[1)]

1) 中国地质大学(北京)地球科学与资源学院,北京,100083;

2) 中国地质大学(北京) 生物地质与环境地质国家重点实验室,北京, 100083

内容提要:作为一种较为特别的微生物碳酸盐岩类型,核形石以双重属性而著称:① 以不平滑的皮层和较大的大小而常常被解释为微生物成因,从而区别于而成因存在着较大争议的鲕粒,所以,核形石也可以作为一种包覆颗粒类型;② 作为微生物碳酸盐岩的一种类型而被归为相互不连接的球状叠层石,因为核形石形成在围绕着核心的序列式纹层化作用过程之中,并且表现为球形或椭球型的生物沉积构造。在山西繁峙茶坊子剖面寒武系苗岭统张夏组块状鲕粒滩相灰岩的顶部,密集发育着厘米级别大小的高能泥晶核形石,核形石灰岩的厚度接近1 m,从而组成一个块状鲕粒滩相灰岩之上特征性的核形石灰岩帽。该层厚度较小的(小于1 m)核形石灰岩中的核形石,具有以下特征:① 厘米级别的大小(1至3 cm);②球形或椭球形的形态学特征;③核形石皮层主导性的泥晶和少量的微亮晶构成;④核形石皮层中较高密度保存的丝状蓝细菌鞘化石;⑤核形石间特别的凝块基质,以及明显的丝状蓝细菌鞘化石构成的凝块。尽管穿越成岩作用过滤器去解释古代核形石复杂的形成机理将存在着巨大的挑战,也尽管形成这些核形石复杂的生物膜钙化作用机理还没有得到完全而且准确的了解,但是,山西省繁峙县茶坊子剖面张夏组顶部的核形石,壮观的宏观特征,核形石皮层中直接的微生物化石证据,尤其是在核形石内较为丰富的丝状蓝细菌鞘化石,使其成为一个了解光合作用生物膜建造核形石的典型实例,而且成为了解发育在高能鲕粒滩相灰岩之上最为特别的"藻坪"沉积的一个较为典型实例。

关键词:丝状蓝细菌钙化鞘化石;核形石;张夏组;寒武系苗岭统;茶坊子剖面;山西省繁峙县

核形石(Oncoids),一个被Heim在1916年所构筑的术语,是一种特别的而且具有双重属性的微生物碳酸盐岩(Tucker and Wright, 1990; 梅冥相等, 1997; 梅冥相, 2007; Védrine et al., 2007; Flügel, 2010; Jones, 2011; 杨仁超等, 2011; Liu Wei et al., 2012; Zaton et al., 2012; Han Zuozhen et al., 2015; 张文浩等, 2014; Pederson et al., 2015; Wilmeth et al., 2015; Lozano et al., 2016; Pretkovic' et al., 2016; 齐永安等, 2014, 2016, 2017a, b)。首先,核形石可以作为一种包覆颗粒的类型,而且以扰动和不平滑的圈层、相对于鲕粒较大的大小而意味着明显的微生物成因,从而区别于成因还存在着较大争议的鲕粒(梅冥相,2012a;Plée et al., 2010; Pacton et al., 2012; Woods, 2013; Siahi et al., 2017; O'Reilly et al., 2017; Diaz et al., 2017; Diaz and Eberli, 2019);其次,作为一种形成在围绕着核心的序列式纹层化作用过程之中、并且表现为球形或椭球型的生物沉积构造,核形石还具有与叠层石(曹瑞骥和袁训来, 2006;Flügel, 2010; Riding, 2000, 2011a, b; Bosak et al., 2013; 梅冥相等, 2016; Peters et al., 2017)相似的沉积学属性。

基于与藻类生物相关的沉积和化石的理念,前苏联地质学家曾经将核形石与凝块石统称为微植石(Microphytolite)而区别于叠层石,杜汝霖(1992)还将凝块石(Thrombolite)等同于花纹石(Catagraphite),也认为微植石是核形石和花纹石的总称;再者,古生物学家曾经采用林奈法分类将核形石划分为3个亚类并进一步划分为十个群[详见杜汝霖(1992)的总结],如:具同心纹层构造的核形石(以 *Osagia* 为代表)、具放射状构造的核形石(以 *Asterrospheroides* 为代表)、具同心纹层和放射状构造的核形石(以 *Pilisphaeroides* 为代表)。在基于林奈

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作者简介:梅冥相,男,1965年生,教授,主要从事沉积学和地层学研究与教学,Email: meimingxiang@263.net。

法的叠层石分类体系中(曹瑞骥和袁训来, 2006),与隐藻叠层石属(*Cryptpzoon Hall* 1883)一起,较为典型的球形核形石曾经被描述为奥萨季叠层石属(*Osagia* Twenhofel 1919),它们一起构成球叠层石纲(Sphaerati)。这些富有智慧的研究和认识,为我们对核形石的观察与研究提供了许多重要的研究线索与思考途径。但是,在解释和描述叠层石之类的微生物碳酸盐岩成因的过程中,使用了上百年的"隐藻(Cryptozoon)"概念,随着蓝绿藻的生物学属性被修订为蓝细菌(Krumbein, 1979, 1983; Brock et al., 1994),长期使用的"藻席(Algal mat)"应该更加准确地定义为"微生物席(Microbial mat)"(Gerdes et

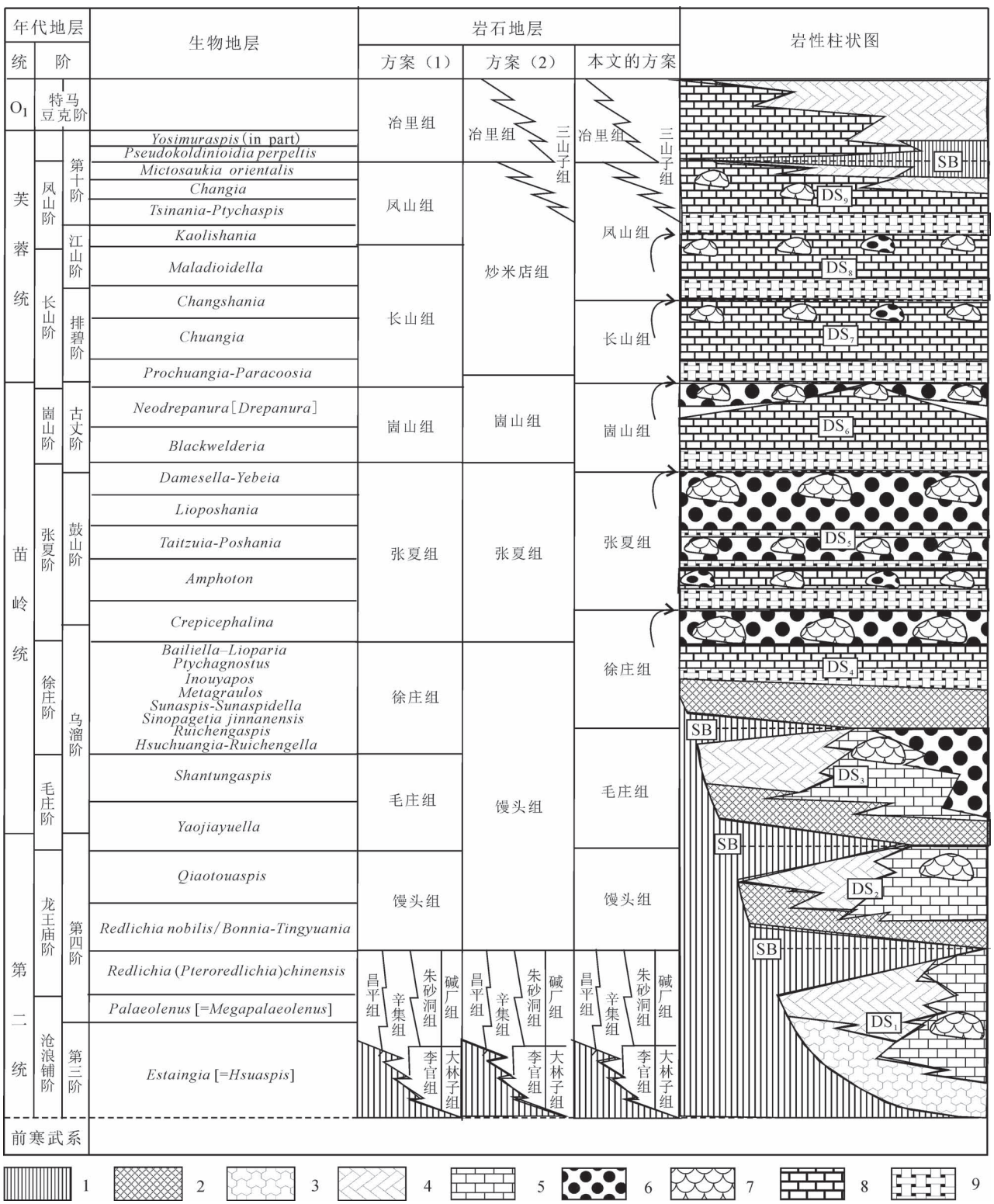


图 1 华北地台寒武纪沉积序列

Fig. 1 Diagram showing the sedimentary succession of the Cambrian in North-China Platform

三叶虫生物地层序列引自彭善池(2009);岩石地层划分方案(1)引自卢衍豪等(1994)、Meng Xianghua 等 (1997)、冯增昭等(1990, 2004),方案(2)引自项礼文等(1999),本文采用的方案沿用方案(1)并基于沉积相序列的层序地层划分予以修改,即华北地台寒武系大致可以划分为 9 个三级层序(DS_1至DS_9),包含着两种类型的层序界面即暴露间断面构成的层序界面(SB)和淹没不整合型层序界面(箭头所指)。图例的含义分别是:1—地层缺失;2—海岸萨布哈相红层泥岩地层;3—潮上砂泥坪相砂泥岩地层;4—潮坪相白云岩地层;5—浅缓坡相灰岩地层;6—鲕粒滩相灰岩地层;7—微生物碳酸盐岩生物丘;8—中至深缓坡相泥灰岩和灰岩地层;9—陆棚相钙质泥岩

Biostratigraphical succession of Trilobites is adapted from Peng Shanchi (2009&). The first sachem (1) for the lithostragraphic division is adapted from Lu Yanhao et al. (1994&), Meng Xianghua et al. (1997), Feng Zengzhao et al. (1990&, 2004&); the second (2) is adapted from Xiang Liwen et al. (1999&); and the sachem (3) is used in this paper, which is amend from the sachem (1) on the basis of the sequence-stratigraphic division according to the succession of sedimentary facies. Nine third-order sequences are discerned in the Cambrian System in the North-China Platform (from DS_1 to DS_9), and these sequences are divided two types of sequence boundaries, i.e. the boundary that is marked by the exposure punctuated surface and the boundary that is characteristic of the drowning unconformity surface. The meaning of legends is respectively as follow: 1—stratigraphic hiatus; 2—strata composed of mudstones of the red bed belonging to the coastal sabakha; 3—strata constituted of sandy mudstones of the supratidal; 4—strata of tidal-flat dolostones; 5—strata of limestones of the shallow ramp; 6—strata of limestones of the ooid-grain bank; 7—bioherms made up of microbial carbonates; 8—strata of limestones and marl of the deep to middle ramp; 9—strata of calcareous shales of the shelf

al., 1994; Gerdes, 2010;梅冥相和孟庆芬, 2016;梅冥相, 2011a, 2012b, 2014, 2017),所以,“微植石(Microphytolite)”的概念也应该抛弃,因为核形石之类的碳酸盐岩沉积主要是有机矿化而不是生物矿化作用过程的产物(Perry et al., 2007;梅冥相和孟庆芬, 2016;梅冥相, 2011a, 2012a, 2012b, 2014, 2017),从而不能够作为直接的微生物化石。就像鲕粒可能形成于复杂的微生物膜钙化作用(梅冥相, 2012a; Plée et al., 2010; Pacton et al., 2012; Woods, 2013;代明月等, 2014; Siahi et al., 2017; O'Reilly et al., 2017; Diaz et al., 2017; Diaz and Eberli,2019),也像鲕粒那样产出和分布在前寒武纪到今天的海水和淡水环境之中,核形石本身确切的形成机理、以及与鲕粒形成机理和产出特征之间的差异,还存在着很多需要进一步研究才能得到合理阐释的科学问题;虽然曾经将核形石与鲕粒作为同一种成因过程的变异体,而且进一步认为是同一过程的产物,即在同心层状组织的基质中的碳酸盐沉淀作用产物,这样的碳酸盐沉淀作用围绕一个共同的细胞或细胞集落构成的中心而形成(Gerdes et al., 1994)。

山西省繁峙县茶坊子剖面寒武系苗岭统张夏组顶部,厘米级别大小的核形石,密集发育在淹没不整合型三级层序(Gómez and Fernández-López, 1994; Schlager, 1989, 1998, 1999;梅冥相和梅世龙, 1997;梅冥相, 1996, 2010, 2011b;马永生等, 2017)的强迫型海退体系域(Hunt and Tucker, 1992; Helland-Hansen and Gjelberg, 1994;梅冥相, 2000; Schlager and Warrlichw, 2009;梅冥相, 2010; Desjardins et al., 2012; Samanta et al., 2016)顶部,构成一个较为典型的“藻坪”沉积(沙庆安等, 1998),从而成为三级海平面下降阶段最晚期的沉积记录(Schlager and Warrlichw, 2009)。特别的层序地层学位置所表征的宏观产出特征,以及特别的微观组构,尤其是在核形石皮层中较高密度产出而且保存较好的多样化丝状蓝细菌鞘化石(Riding, 1991, 2000, 2011b),意味着这些核形石形成于较为典型的光合作用生物膜或微生物席的钙化作用,从而成为一个较为壮观的沉积学现象,为了解形成核形石形成于复杂的生物膜(Flemming and Wingender, 2010; Flemming et al., 2010, 2016)、以及构成生物膜的细胞外聚合物质(Dupraz et al., 2009, 2011; Decho, 2010; Tourney and Ngwenya, 2014; Decho and Gutierrez, 2017)的钙化作用,提供了一个较为典型的实例。

1　地质背景

华北地台在寒武纪接受沉积的时间相对较晚,大致开始于第二世的晚期,而且寒武纪地层超覆在不同时代的前寒武纪地层之上,从而形成一个类似于北美地台的“巨型不整合面”(Peters and Gaines, 2012),并且在华北地台形成一个特别的寒武纪沉积序列(图 1;乔秀夫等,1990;章雨旭等,1990;梅冥相等, 1997b;史晓颖等, 1997;Meng Xianghua et al., 1997;柳永清等,1999;章雨旭, 2001;冯增昭等, 1990, 2004; Mei Mingxiang et al., 2005; Lee

and Chough, 2011; 梅冥相, 2011b; 陈小炜等, 2013; 马永生等,2017; 梅冥相等,2017; 李振生等, 2018; 王龙等, 2018),即从寒武纪第二世红层与碳酸盐岩混合沉积、经苗岭世鲕粒滩主导的碳酸盐台地序列变化到芙蓉世碳酸盐泥所主导的碳酸盐台地沉积序列;基于沉积相序列及其所代表的旋回性(Catuneanu, 2006; 梅冥相, 2010; Catuneanu et al., 2011),可以将华北地台寒武纪沉积序列划分为 9 个三级层序(图 1 中 DS_1的至 DS_9)。

在华北地台,张夏组,与毛庄组、徐庄组、和崮山组一起大致构成了苗岭世(彭善池和赵元龙, 2018)的地层(图 1),代表一个从红层与碳酸盐岩的混合潮坪沉积(毛庄组和徐庄组下部)到鲕粒灰岩主导的缓坡型台地沉积的变化序列(梅冥相和梅世龙, 1997; Meng Xianghua et al., 1997; 冯增昭等, 1990, 2004; 彭善池, 2006; 梅冥相, 2011b; 陈小炜等, 2013; 马永生等, 2017; 王龙等, 2018);更为特征的是,在徐庄组、张夏组和崮山组的顶部集中发育鲕粒滩相沉积(梅冥相和梅世龙, 1997; Meng Xianghua et al., 1997; 沙庆安和江茂生, 1998; 梅冥相,2011b; 陈小炜等, 2013; 马永生等, 2017; 王龙等, 2018),较为清楚地表明鲕粒滩的发育在三级相对海平面下降过程之中(图 1 的 DS_4至 DS_6),代表着强迫型海退过程的产物(Hunt and Tucker, 1992; Helland-Hansen and Gjelberg, 1994; 梅冥相和杨欣德, 2000; Schlager and Warrlichw, 2009; 梅冥相, 2010; Desjardins et al., 2012; Samanta et al., 2016),反映了较高的沉积物生产作用、较慢的侵蚀作用以及较慢的海平面下降速率的基本特点(Schlager and Warrlichw, 2009)。

在三级层序的强迫型海退过程之中发育的大面积分布的鲕粒滩,代表着类型多样的寒武纪碳酸盐台地类型(Williams et al., 2011; Pratt et al., 2012)中的一种新的碳酸盐台地类型,即鲕粒所主导的浅

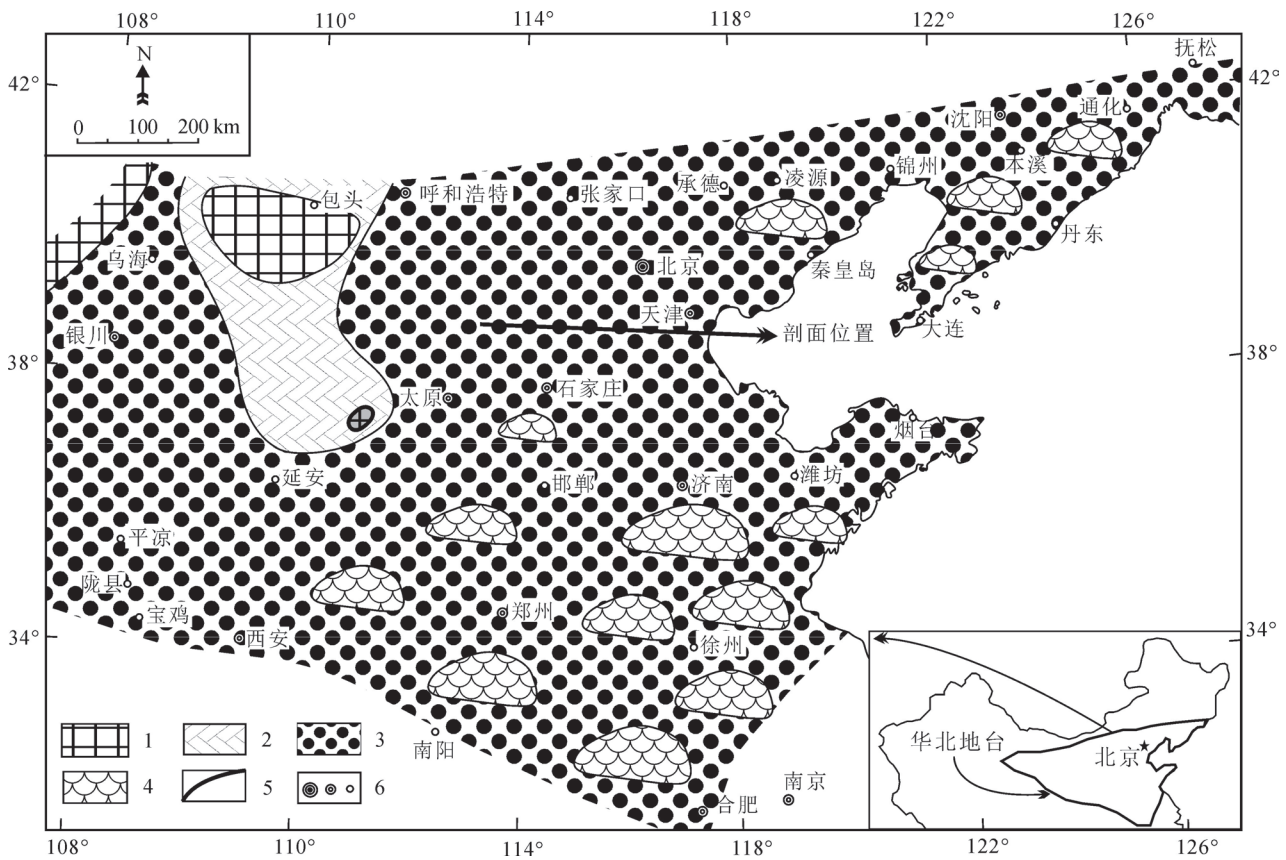


图 2 华北地台寒武纪苗岭世张夏组沉积期晚期的沉积格局

Fig. 2 Diagram showing the sedimentary pattern for the late dopostional period of the Zhangxia Formation of the Cambrian Miaolingian in the North-China Platform

箭头所指代表山西省繁峙县茶坊子剖面的位置;图例的含义分别是:1—古陆; 2—潮坪相;3—鲕粒滩相;4—生物丘;5—相界线;6—城市

The arrowed refers to the location of the Sandaogou section in the western part of Liaoning province. The meaning of legends is respectively as follow: 1—oldland; 2—tidal-flat facies; 3—ooid grain bank; 4—bioherm; 5—facies boundary; 6—city

海碳酸盐陆架为特征的一种特别的碳酸盐台地,其基本特征是:①浅海陆架被颗粒质的鲕粒沉积物大面积覆盖;②向海一侧为缓坡、向陆一侧为潮坪(图2;冯增昭等, 1990, 2004; Meng Xianghua et al., 1997; 马永生等, 2017; 王龙等, 2018),而且在大面积分布的浅水高能陆架或浅缓坡上发育的鲕粒滩中,局部发育类似于"藻坪"(沙庆安和江茂生, 1998; 沙庆安, 1999)或"微生物礁"(Riding, 2000, 2002; 韩作振, 2009; Pratt et al., 2012; Chen Jitao et al., 2014; Lee et al., 2015; Lee and Riding, 2018)的微生物碳酸盐岩构成的生物丘(梅冥相, 2011b; 赫云兰等, 2012; 马永生等, 2017)。

山西省繁峙县茶坊子剖面的寒武系张夏组,组成一个包含着 3 个四级亚层序(图 3)的三级沉积层序(图 1 中的 DS_5),它们的顶和底界面均以较为典型的淹没不整合面组成的层序界面(Gómez and Fernández-López, 1994; Schlager, 1989, 1998, 1999; 梅冥相, 1996, 2010, 2011b; 马永生等, 2017),这些界面的基本特征表现为具有凝缩性质的中至深缓坡相灰岩和泥灰岩地层直接覆盖在鲕粒滩相灰岩地层之上(图 3 中的照片(a)和(b)所示),而且在这些凝缩性质的中至深缓坡相灰岩和泥灰岩地层中常常发育着竹叶状砾屑灰岩构成的风暴沉积(孟祥化等, 1986; Meng Xianghua et al., 1997; 柳永清等, 1999; Myrow et al., 2004; Pratt and Bordonar, 2007)。下文将要介绍的核形石,正是发育在张夏组构成的三级层序(图 1 中的 DS_5)的强迫型海退体系域(Hunt and Tucker, 1992; Helland-Hansen and Gjelberg, 1994; 梅冥相和梅仕龙, 1997; 梅冥相和杨欣德, 2000; Schlager and Warrlichw, 2009; 梅冥相, 2010; Desjardins et al., 2012; Samanta et al., 2016)顶部,构成块状高能鲕粒滩相灰岩之上的一个特别的核形石灰岩帽或覆盖层,代表着一个高能泥晶核形石的典型实例和壮观的沉积学现象。

2　核形石的宏观特征

在山西省繁峙县茶坊子剖面,张夏组顶部的块状鲕粒滩相灰岩(图 4a; 沙庆安, 1999)地层组成了三级层序强迫型海退体系域(Hunt and Tucker, 1992; Helland-Hansen and Gjelberg., 1994; 梅冥相, 2000; Schlager and Warrlichw, 2009; 梅冥相, 2010; Desjardins et al., 2012; Samanta et al., 2016),在其顶部发育一层厚度 1 m 左右的核形石灰岩(图 4b)。这一层核形石灰岩,不发育鲕粒,但是发育着许多风化成灰黄色的钙泥质条带和结核,表现为泥晶生物丘的外貌特征,而且以一个突变式的硬底面发育在块状鲕粒灰岩之上(图 3b)。

这一层核形石灰岩主要为宏观和巨型核形石构成(图 4c;Flügel, 2010; Pretkovic' et al., 2016),表现出以下特征:①较小的厚度(小于 1 m;图 3 的照片(b)和图 4b),组成一个特别的块状鲕粒滩相灰岩的核形石灰岩帽(或覆盖层);②厘米级别的大小(图 4c),多在 1 至 3 cm 之间,而且大小较为均匀,在其间可见少量毫米级别的核形石;③球形或椭球形的形态学特征,并表现出明显的基质支撑的特点(图 4c;Wilmeth et al., 2015),因为巨型与宏观核形石彼此之间很少直接接触;④主导性的纹层状泥晶纹层构成,无数个微细的泥晶纹层(微米级别)围绕着核心并表现为重复性的序列式生长,而且这些微细纹层相对较为连续和近似平滑,核形石的核心多为凝块和生物碎屑构成,表现出纹层状的高能核形石的特点(图 4c;Zaton et al., 2012; Han Zuozhen et al., 2015; Pretkovic' et al., 2016),在表现出可迁移的包覆颗粒属性(Tucker and Wright, 1990; 梅冥相等, 1997; 梅冥相, 2007; Védrine et al., 2007; Flügel, 2010; Jones, 2011; 杨仁超等, 2011; Liu Wei et al., 2012; Mei et al., 2012; Zaton et al., 2012; 张文浩等, 2014; Han Zuozhen et al., 2015; Pederson et al., 2015; Wilmeth et al., 2015; Lozano et al., 2016; Pretkovic' et al., 2016; 齐永安等, 2017a, b)的同时,也表现出较为明显的球状叠层石的基本属性(曹瑞骥和袁训来, 2006;Flügel, 2010; Riding, 2000, 2011a, 2011b; Bosak et al., 2013; 梅冥相等, 2016; Peters et al., 2017);⑤特别的基质构成,如图 3 的照片(b)所示,核形石直接生长在鲕粒滩相灰岩之上,但是,如图 4c 所示,在核形石之间的填充基质之中几乎见不到鲕粒的影子,除了小型的核形石以外,更多是凝块和三叶虫生物碎屑或三叶虫化石;严格说来,这些砾石级别的核形石的集中产出本身,代表着一种特别的沉积构造(钟建华和梁刚,2009)。

3　核形石的微观特征

山西省繁峙县茶坊子剖面张夏组顶部的巨型和宏观核形石,在低倍显微镜下,核形石皮层表现为围绕着核心致密分布的、而且相对不太平滑和连续的暗色泥晶和微亮晶主导的微细纹层(图 5a 至 5c),

类似于叠层石中的亮层与暗层(Ka mierczak et al., 2015)。这些核形石皮层中的纹层,相对于鲕粒皮层(梅冥相, 2012a; Plée et al., 2010; Pacton et al., 2012; Woods, 2013; 代明月等, 2014; Siahi et al., 2017; Diaz et al., 2017; O'Reilly et al., 2017)来讲要厚得多(数十微米的厚度,多为 20~40 μm),而且围绕着核心表现为重复性序列式的纹层化作用过程,从而具有明显的叠层石属性(曹瑞骥和袁训来, 2006; Flügel, 2010; Riding, 2000, 2011a, 2011b; Bosak et al., 2013; 梅冥相和孟庆芬, 2016; Peters et al., 2017),很明显,微亮晶纹层相对较少而且分布更加不连续。核形石的核心,包括不具纹

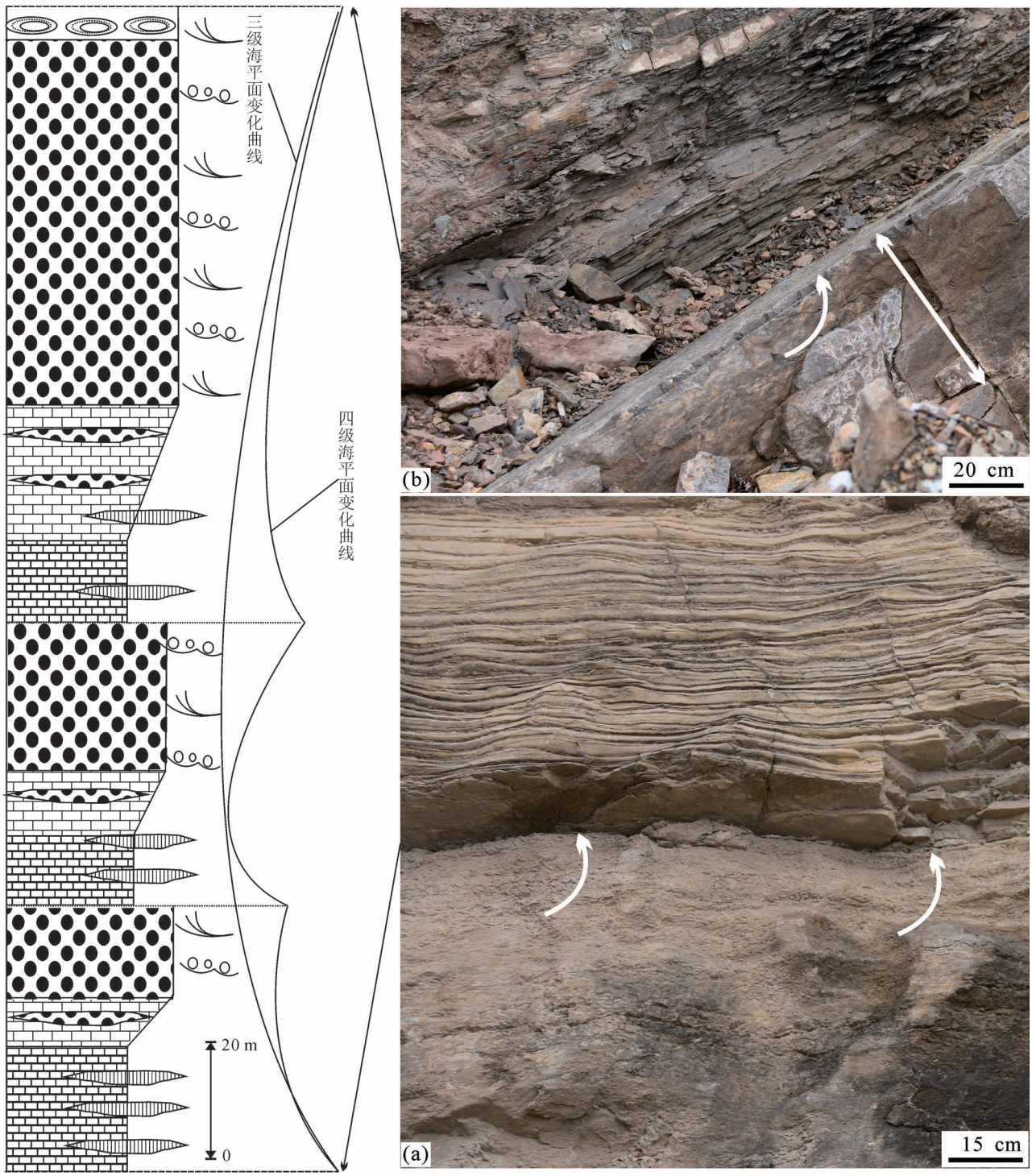


图 3 山西省繁峙县茶坊子剖面苗岭统张夏组的沉积相序列

Fig. 3 Diagram showing the succession of sedimentary facies for the Zhangxia Formation of the Cambrian Miaolingian Series at the Chafangzi section in Fanshi county of Shanxi province

剖面位置如图 2 所示,一个总体向上变浅的沉积相序列构成了一个三级层序,并可以进一步划分为 3 个四级亚层序。图例代号的含义分别是:1—鲕粒滩相灰岩地层;2—中至浅缓坡相灰岩地层;3—中至深缓坡相灰岩和泥灰岩地层;4—核形石;5—竹叶状砾屑灰岩构成的风暴沉积;6—交错层理;7—冲刷面;8—层序界面;9—亚层序界面。照片(a)代表三级层序的底界面(箭头所指);照片(b)代表三级层序的顶界面(箭头所指),其中的双向箭头所示为核形石灰岩

The section location is shown in Fig. 2. An upward-shallowing succession of sedimentary facies makes up a third-order sequence that can be subdivided into 3 subsequences. The meaning of legends is respectively as follow: 1—strata of the ooid-grained bank; 2—strata of limestones of the middle to shallow ramp; 3—strata of limestones of the middle to deep ramp; 4—oncoid; 5—storm deposits that are marked by flat-pebble conglomerates; 6—cross-bedding; 7—scouring surface; 8—sequence boundary; 9—subsequence boundary. Image (a) shows the bottom sequence boundary (the arrowed) of the third-order sequence; Image (b) shows the top sequence boundary (the arrowed) of the third-order sequence, within which indicates a bed of oncolitic limestone (represented by the arrow of double direction)

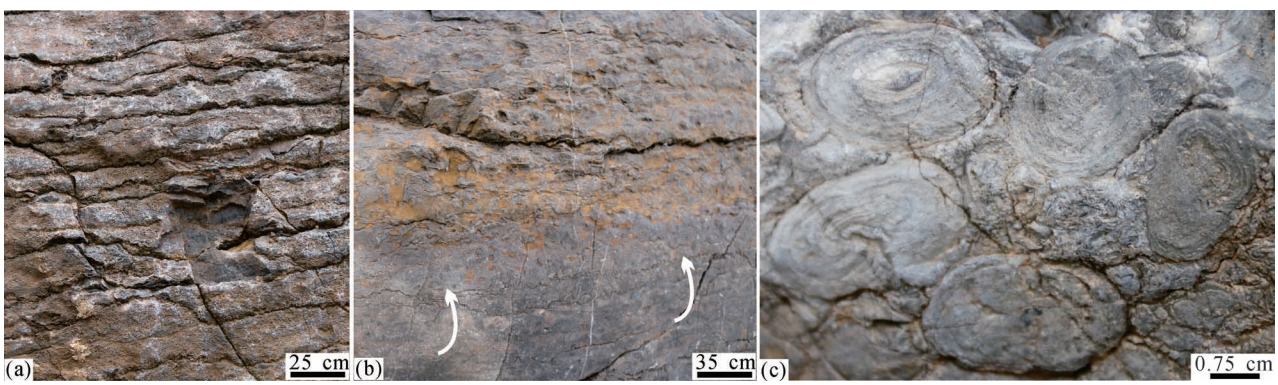


图 4 山西省繁峙县茶坊子剖面苗岭统张夏组顶部块状鲕粒滩相灰岩的核形石灰岩帽及其相关沉积

Fig. 4 Images showing the cap of oncolitic limestones and its relative deposits in the top part of massive oolitic grainstones of the Zhangxia Formation of the Cambrian Miaolingian Series at the Chafangzi section in Fanshi county of Shanxi province

(a)块状鲕粒滩相灰岩;(b)生长在块状鲕粒灰岩之上的泥晶生物丘状的核形石灰岩帽,二者之间为一个类似于硬底面的突变式界面(箭头所指);(c)巨型与宏观核形石

(a) massive oolitic grainstone of the carbonate bank; (b) micro-bioherm like cap on the massive oolitic grainstone of the carbonate bank, and their boundary is marked by a hardground (the arrowed); (c) mege- or macrooncoids

层的泥晶凝块(图 5a)和三叶虫化石(图 5b);核形石的外部边界,多较为明显,局部为锯齿状而表现出受到磨损的特点(图 5a 至 5c)。

同时,在泥晶核形石的纹层状皮层之中,较为典型的微亮晶所填充窗格状孔隙(图 5a 至 5c),表现为形态不规则的、大小在 0.2 至 0.5 mm 的浅色窗格状组构,这样的组构有时候断断续续地沿着纹层分布,但是,多数切割纹层;这样的窗格状孔隙类似于 Wilmeth 等(2015)在蒙古西部早寒武世 Bayan Gol 组核形石中所描述的现象,类似的窗格状组构在现代黄石国家公园的蓝细菌微生物席所构成的叠层石中被解释为光合作用产生的氧气气泡的残余物(Bosak et al., 2010;Pepe-Ranney et al., 2012),由于这些窗格状孔隙被较细的垂向丝状体所分开,所以被 Mata 等 (2012) 进一步定义为"砂滤状(hourglass structures)"构造。更为特别的是,在低倍显微镜下表现出的致密泥晶纹层状的核形石皮层,在高倍显微镜下表现出明显的丝状蓝细菌鞘化石构成(图 5d)。

进一步观察表明,茶坊子剖面张夏组核形石的致密泥晶皮层(图 5a—c、图 6a、d)中,表现出高密度较好保存的丝状蓝细菌化石构成(图 5d、图 6b、e)。这些丝状蓝细菌鞘化石,长度可以达到 0.5 mm,直径为 10 μm 左右,具有厚度均匀(1~2 μm)的暗色泥晶壁,从而代表着丝状蓝细菌鞘活体钙化作用的残余物,而且代表着一个直接与大气圈二氧化碳浓缩作用机制(CCMs)相联系的生态生理学机制(Kah and Riding, 2007; Riding, 2000, 2011c),正是这种

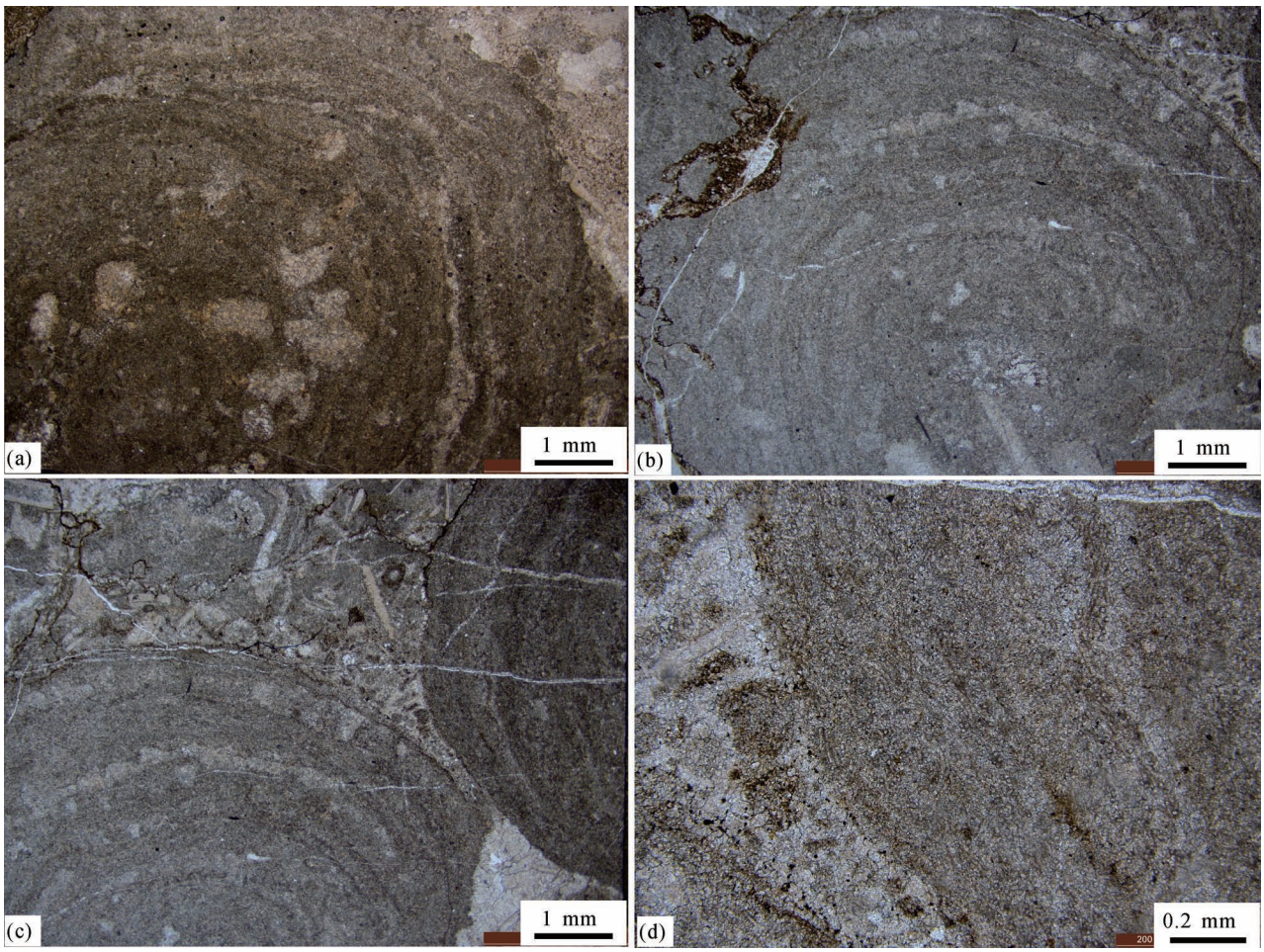


图 5 山西省繁峙县茶坊子剖面苗岭统张夏组顶部核形石的总体微观特征

Fig. 5 Images showing the general microscopic feature of oncoids in the top part of the Zhangxia Formation of the Cambrian Miaolingian Series at the Chafangzi section in Fanshi county of Shanxi province

(a)至(c),厘米级别的巨型和宏观核形石,为包含着窗格状组构的致密泥晶纹层和少量微亮晶纹层构成核形石的皮层,核形石的核心包括球状泥晶凝块(a)和三叶虫碎屑(b),核形石间的填充基质包括泥晶、三叶虫生物碎屑和暗色泥晶构成的凝块(c);在高倍显微镜下,核形石皮层的致密泥晶构成之中发育着较为清楚的丝状蓝细菌鞘化石(d)

(a) to (c), the centimeter-level mega- and macrooncoid whose cortex is composed of micritic and few microspar lamination as well as the fenestrae fabric, the nuclei of oncoids is made up of both the spherical micritic clot (a) and bioclast of trilobite (b), the matrix (c) between ooids is consituted by the clot, the bioclast of trilobite and the micrite. Image (d) depicts the clear sheath fossil of the filamental cyanobacteria within the cortex of oncoid enlarged from one oncoid as shown in image (c)

特殊的蓝细菌鞘的活体钙化作用形成了丝状蓝细菌鞘化石的轮廓;内部被亮晶方解石交代的管可能是蓝细菌细胞列(香毛簇)的降解作用残余物(Riding, 1991, 2000, 2011c);因此,这些缠绕状的丝状体,确实可以归为"葛万菌(*Girvanella*)"化石组合的构成分子。

虽然类似于葛万菌(*Girvanella*)的缠绕状丝状蓝细菌鞘化石还被类比于现代的伪枝菌(*Scytonema*;齐永安等, 2017b),但是,主流认识还是将其类比于现代的织线菌(*Plectonema*;Riding, 1991;De los Ríos et al., 2015);再者,如图 6b 和 6e 所示,茶坊子剖面张夏组核形石皮层中的丝状蓝细菌鞘化石,总体上不具有成束产出的特点,所以不发育可以进一步类比于今天的微鞘菌(*Microcoleus*;Riding, 1991; Liu et al., 2016)或鞘线菌(*Coleofasciculus*; Frantz et al., 2015)的束线菌(*Subtifioria*)化石,主要包括着两种类型:①那些缠绕状的丝状体,可以类比于现代的织线菌(*Plectonema*; Riding, 1991; De los Ríos et al., 2015),是较为典型的葛万菌(*Girvanella*)化石(图

6b),而且在核形石间的微凝块中,这样的丝状蓝细菌鞘化石以更大的密度缠绕(图 6a 和 6c);②那些不具有缠绕状的特点的丝状蓝细菌化石,可以类比于现代的第谷菌(*Tychonema*; De los Ríos et al., 2015)(图 6e),应该代表着葛万菌组合(*Girvanella* Group; Riding, 1991)的一个新类型化石。

更为特别的是,与黄石国家公园的现代硅质叠层石中的窗格状构造(Bosak et al. 2010; Pepe-Ranney et al. 2012; Mata et al., 2012)稍微不同的是,茶坊子剖面张夏组核形石皮层中的窗格状孔隙,发育在相互缠绕而且可以类比于现代织线菌(*Plectonema*; Riding, 1991; De los Ríos et al., 2015)的葛万菌(*Girvanella*)(图 6b)、以及不缠绕的而且可以类比于现代第谷菌(*Tychonema*; De los Ríos et al., 2015; 图 6e)的管状或丝状钙化蓝细菌鞘化石构成的网状体之中;这些丝状蓝细菌鞘化石,在核形石皮层的致密泥晶基质之中大多围绕着核形石的核心呈切线式的分布。

最为重要的是,在那些较为密集地发育着窗格状孔隙的核形石皮层中,也同样发育着毫米级别的暗色泥晶组成的凝块(图 7a),这些凝块在高倍显微镜下表现出较为致密分布而且保存着较好的丝状蓝细菌鞘化石构成(图 7b)。其中的丝状蓝细菌鞘化石,由于表现为非缠绕状,属于那些可以类比于现代第谷菌(*Tychonema*; De los Ríos et al., 2015)的管状或丝状钙化蓝细菌鞘化石,似乎表现为近似平行的致密排列的方式垂直生长,丝状体化石的直径多为 10 ~20 μm,长度超过 0.5 mm,具有厚度均匀(1~2 μm)的暗色泥晶壁,从而代表着丝状蓝细菌鞘活体钙化作用的残余物,内部被亮晶方解石交代的管可能是蓝细菌细胞列(香毛簇)的降解作用残余物(Riding, 1991, 2000, 2011c)。如果说图 6a 和图 6c 所示的填充在核形石基质中的致密泥晶基质的凝块为缠绕状的葛万菌(*Girvanella*)化石所组成的话,核形石皮层中的这些暗色泥晶基质的凝块,似乎更多为非缠绕状的、而且可以类比于现代第谷菌(*Tychonema*; De los Ríos et al., 2015; 图 6d 和 6e)的管状或丝状钙化蓝细菌鞘化石所构成;在核形石内部残留着谜一样的可能的胞网菌(*Bacinella*; Védrine et al., 2007; Schlagintweit et al., 2013)状组构代表的钙化蓝细菌残余物(图 7a)更加说明了这一点,进一步说明了形成这一层核形石灰岩帽对应着多重状微生物席的特征(Kaz'mierczak et al., 2015; De los Ríos et al., 2015)。

同样,在核形石的暗色泥晶所主导的皮层之中(图 7a),也同样发育着缠绕状的葛万菌(*Girvanella*)化石(图 8),这些长度可以达到毫米级别(超过 0.5 mm)、直径为 10 ~20 μm 的丝状蓝细菌鞘化石,具有厚度均匀(1~2 μm)的暗色泥晶壁而代表着丝状蓝细菌鞘活体钙化作用的残余物,内部被亮晶方解石交代的管可能是蓝细菌细胞列(香毛簇)的降解作用残余物(Riding, 1991, 2000, 2011c),而且以保存较好的较高密度分布在构成核形石皮层的泥晶和微亮晶基质之中;与构成核形石间的基质中的凝块的葛万菌化石构成(图 6a 和 6c)稍微不同的是,核形石皮层之中的这些缠绕状的葛万菌化石,组成了沿着围绕着核形石核心的方向呈切线状排列生长的泥晶纹层,这样的泥晶纹层可以延伸到数毫米的长度(图 7a)。

还需要特别之处的,山西省繁峙县茶坊子剖面的张夏组顶部块状鲕粒滩相灰岩的核形石帽(图 3),特别的宏观特征(图 4)以及微观构成(图 5 至图 8)表明,尽管直接生长和发育在块状鲕粒滩相灰岩之上(图 3b 和图 4b),在这一层厚度为 1 m 左右的核形石灰岩帽之中,确实没有见到鲕粒的痕迹,如果可以理解为核形石颗粒滩相(沙庆安,1999)灰岩的话,较为典型地表明了核形石灰岩帽生长和发育的相对独立性。

4　讨论

山西省繁峙县茶坊子剖面的张夏组顶部块状鲕粒滩相灰岩的核形石帽(图 3),集中发育在三级沉积层序顶部的强迫型海退体系域的顶部(图 3b 和图 4b),以相对独立的生长和发育特征形成一层厚度为 1 m 左右的核形石灰岩帽而覆盖在块状鲕粒滩相灰岩之上,组成海平面相对下降阶段最晚期的沉积;纹层状泥晶和微亮晶纹层构成的巨型与宏观椭球状和球状泥晶核形石,具有厘米级别大小(图 4c 和图 5),不但蕴含着球状叠层石的沉积属性(梅冥相, 2007; Flügel, 2010; Riding, 2011a, 2011c; Bosak et al., 2013; 梅冥相和孟庆芬, 2016; Peters et al., 2017),还具有类似于鲕粒的颗粒属性,最终形成为高度保存着钙化蓝细菌鞘化石(图 6 至图 8)的可迁移砾状颗粒(Wilmeth et al., 2015),而且是形成在海底上的频繁翻滚过程中的高能砾状颗粒(图 5),从而成为较为壮观的沉积学现象。

近年来在华北地台寒武纪核形石的研究中,已经在核形石皮层中发现了普遍发育的蓝细菌鞘化石

(Liu Wei et al., 2012; Wilmeth et al., 2015; Han Zuozhen et al., 2015; 齐永安等, 2016, 2017a, b), 为阐释核形石的微生物成因提供了直接的微生物证据。山西省繁峙县茶坊子剖面张夏组顶部的核形石,特别的致密暗色泥晶和微亮晶组构组成了核形石皮层(图 5a 至 5c),凝块状泥晶构成了核形石间特别的基质(图 5a、5c、6a 和 6d)。在核形石的致密泥晶皮层(图 6、图 7a 和图 8)、核形石皮层中的凝块(图 7a 和 7b)以及核形石间的基质中的凝块(6a 和 6c)之中,均发育着较高密度保存的丝状蓝细菌鞘化石,强烈意味着这些核形石一个明显的微生物成因,这些钙化蓝细菌化石包括:①非缠绕状的丝状蓝细菌鞘化石,表现为可以类比于类似于现代第谷菌(*Tychonema*;De los Ríos et al., 2015)的管状或丝状钙化蓝细菌而成为葛万菌组合(*Girvanella* Group; Riding, 1991)中的一个新类型化石(图 6e 和 7b);②可以类比于现代织线菌(*Plectonema*; Riding, 1991; De los Ríos et al., 2015)的葛万菌之类的丝状

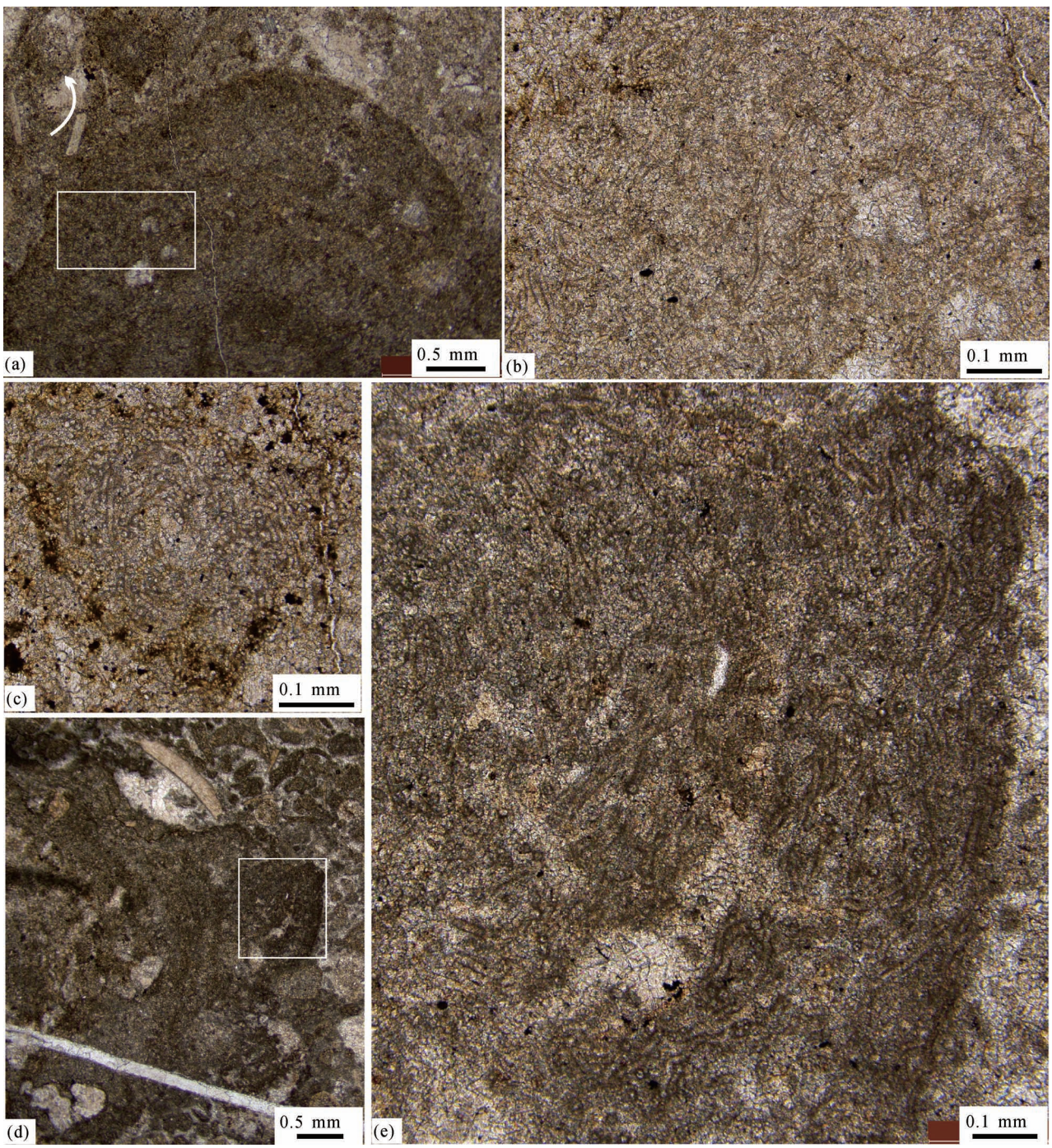


图 6 山西省繁峙县茶坊子剖面苗岭统张夏组顶部巨型核形石中的丝状蓝细菌鞘化石

Fig. 6 Images showing the filamental fossil of the cyanobacteria sheath within oncoids in the top part of the Zhangxia Formation of the Cambrian Miaolingian Series at the Chafangzi section in Fanshi county of Shanxi province

(a)发育着窗格状孔隙的致密泥晶宏观核形石,箭头所指代表了放大为照片(c)的泥晶凝块,矩形框是放大为照片(b)的部分;(b)核形石皮层之中缠绕状丝状蓝细菌鞘化石(葛万菌)构成,对应于照片(a)矩形框所示的泥晶核形石皮层;(c)缠绕状丝状蓝细菌鞘化石(葛万菌)构成的泥晶凝块(照片(a)中的箭头所指);(d)发育着窗格状孔隙和粘附着三叶虫化石的泥晶核形石,矩形框所示部分放大为照片(e);(e)非缠绕状的可以类比于现代第谷菌的丝状蓝细菌鞘化石,对应着照片(d)中的矩形框所示的泥晶核形石皮层。在照片(b)、(c)和(e)中的少量黑点可能为黄铁矿晶体的残余物

(a) one oncoid that is composed of dense micrites and few fenestrae pores, the arrow refers to a micritic clot that is enlarged as the image (c), and the part of micritic oncoidal cortex that is marked by the rectangle is enlarged as the image (b); (b) obvious intertwisted sheath fossils of the cyanobacteria (*Girvanella*) within the micritic oncoidal cortex corresponding the part that is marked by the rectangle in image (a); (c) obvious intertwisted sheath fossils of the cyanobacteria (*Girvanella*) make up one micritic clot as shown as the arrowed in image (a); (d) micritic oncoid with few fenestrae pores and trilobite fossils, the part of micritic oncoidal cortex that is marked by the rectangle is enlarged as the image (e); (e) obvious non-intertwisted sheath fossils of the cyanobacteria (*Tychonema*) within the micritic oncoidal cortex corresponding the part that is marked by the rectangle in image (d). Few black dots in image (b), (c) and (e) probably represent the residues of pyrite crstals

蓝细菌鞘化石(图 6b 和 8);以及③可能的胞网菌(*Bacinella*; Védrine et al., 2007; Schlagintweit and Bover-Arnal, 2013)状组构代表的钙化蓝细菌残余物(图 7a)。由于这些丝状蓝细菌鞘化石多发于在致密泥晶和微亮晶基质之中,也尽管这些丝状蓝细菌鞘化石普遍具有厚度均匀(1~2 μm)的暗色泥晶壁而代表着蓝细菌活体鞘的钙化作用(Kah and Riding, 2007;Riding, 2000, 2011c),我们还是不能够简单地将核形石的形成,直接理解为蓝细菌钙化作用的产物;与在丝状蓝细菌之间代表着光合作用产生的氧气气泡残余物(Bosak et al. 2010; Pepe-Ranney et al., 2012; Mata et al., 2012; Wilmeth et al., 2015)的窗格状孔隙(图 5a 至 5c、图 6a 和 6d、图 7a)一起,应该代表着一个复杂的蓝细菌主导的光合作用微生物膜或微生物席的钙化作用过程(Riding, 2000, 2011b; Dupraz et al., 2009, 2011),因为并非所有蓝细菌所主导的作用微生物席或微生物膜均能够钙化,而且今天的绝大多数微生物席确实没有形成坚硬的岩石(Stal, 2012)。在这些较大的巨型和宏观核形石(图 4c 和图 5a—c)中,主导性的泥晶(暗层)纹层,可以解释为发生在接近活着的蓝细菌纹层底部的黏液中的沉淀作用产物,少量亮晶纹层(亮层)则代表着在异养细菌降解(死亡了的)的蓝细菌纹层中的沉淀作用产物(Kaz′mierczak et al., 2015);总的来讲,这些泥晶所主导的核形石,则更多是发生在接近活着的蓝细菌纹层底部的黏液中的泥晶沉淀作用的产物,这种较早期的泥晶沉淀作用和石化作用,意味着核形石生长相对较强的独立性。

核形石皮层(图 6b、6e 和图 8)、核形石皮层中的凝块(图 7b)以及在基质中的凝块(图 6c)中常见到的黄铁矿颗粒与晶体,说明了形成核形石的微生物沉淀作用(Riding, 2000, 2011b, 2011c)和早期石化作用(Dupraz et al., 2009, 2011),还可能与硫酸盐还原细菌造成的硫酸盐还原反应(Rickard et al., 2017)存在着成因联系,从而进一步表明了在微生物席内碱度发动机(Gallagher et al., 2012)和细胞外聚合物质(Decho, 2010; Tourney and Ngwenya, 2014; Flemming Wingender, 2010; Flemming et al., 2016; Decho and Gutierrez, 2017)构成的有机基质这两个关键要素的紧密耦合,卷入了碳酸盐矿物的原地沉淀作用。进一步讲,由于蓝细菌是最为成功的造席生物(Stal, 2012),蓝细菌作为原始生产者的微生物活动最终造成了细胞外聚合物质(EPS)的生产作用并形成特别的生物膜和微生物席,而且构成生物膜和微生物席 EPS 的硫酸盐还原细菌之类的异养细菌的降解作用,诱发了矿物的沉淀作用(Dupraz et al., 2009, 2011; Bosak et al., 2013),这些复杂的作用过程形成了寒武纪苗岭世泥晶纹层所主导的核形石。

在核形石的致密泥晶皮层(图 6、图 7a 和图 8)、核形石皮层中的凝块(图 7a 和 7b)以及核形石间的基质中的凝块(6a 和 6 c)之中,均发育着较高密度保存的丝状蓝细菌鞘化石。尽管这些丝状蓝细菌具有接近 1 mm 长度,也尽管山西省繁峙县茶坊子剖面的张夏组顶部块状鲕粒滩相灰岩的核形石帽直接发育在鲕粒滩相灰岩之上,横向上还可能与鲕粒滩相灰岩相邻,但是,在这一层厚度为 1 m 左右的核形

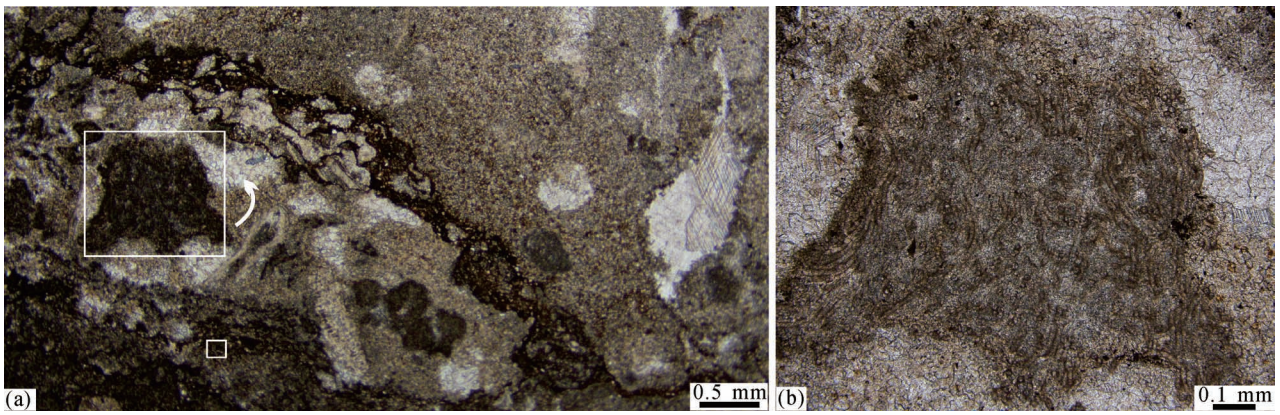


图 7 山西省繁峙县茶坊子剖面苗岭统张夏组顶部巨型核形石中的凝块和窗格状孔隙

Fig. 7 Images showing the clot and the fenestrae pore within the cortex of oncoid in the top part of the Zhangxia Formation of the Cambrian Miaolingian Series at the Chafangzi section in Fanshi county of Shanxi province

(a),左下部为核形石皮层,右上部为核形石间的凝块状泥晶基质,在核形石皮层中发育暗色泥晶组成的形态不规则的毫米级别的凝块(大的矩形框所示)以及可能的胞网菌(*Bacinella*)状组构(箭头所指),小的矩形框所示部分被放大为图 8;(b)照片(a)中的大的矩形框所示部分的放大,表现为致密分布在泥晶基质中的丝状蓝细菌鞘化石构成

(a) the oncoidal cortex (the lower-left) and its matrix (the upper-right part) composed of dense clotted micrites, many large clots (as shown in a large rectangle) within the oncoidal cortex, and the arrowed refers to the possible *Bacinella* fabiric, the part of the oncoidal cortex that is marked by the small is enlarged as Fig. 8; (b) the enlarge of a large colt within the oncoidal cortex (as shown in a large rectangle within image (a)), which clearly demonstrate a composing of the sheath fossil of filamental cyanobacterias

石灰岩帽之中确实没有见到鲕粒的痕迹,不但表明了核形石灰岩帽生长和发育的独立性而形成一种类似于“藻坪”(沙庆安和江茂生,1998)沉积,而且还表明了寒武纪时期的丝状蓝细菌还不具有捕获砂级大小颗粒的能力(Suàrez-Gonzàlez et al., 2014; Frantz et al., 2015)。

更有可能的情况是,山西省繁峙县茶坊子剖面张夏组上部块状鲕粒滩相灰岩顶部的核形石灰岩帽,代表着相对较厚的蓝细菌微生物席的建造物(Gerdes et al., 1994; Gerdes, 2010; Arp et al., 2012; Stal, 2012),主要表现在组构极强的非均质性之上。具体来讲,砾状大小的泥晶主导的纹层状核形石(图 4c),多表现为漂浮状产出在凝块状泥晶基质之中(图 5a、5c、6a 和 6d),不管是核形石皮层中的凝块(图 7b)还是基质中的凝块(图 6c),与核形石皮层中较高密度分布的丝状蓝细菌鞘化石构成(图 6、图 7a 和图 8)一样,表现为明显的光合作用生

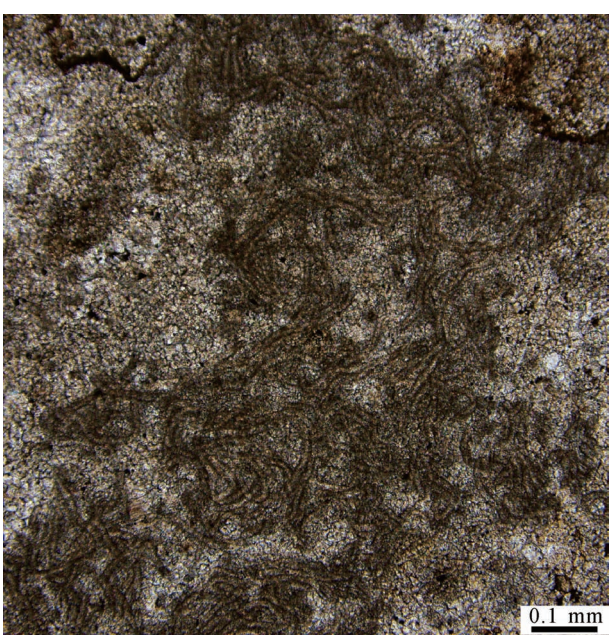


图 8 山西省繁峙县茶坊子剖面苗岭统张夏组顶部巨型核形石皮层中的葛万菌

Fig. 8 Images showing the *Girvanella* within the cortex of oncoid in the top part of the Zhangxia Formation of the Cambrian Miaolingian Series at the Chafangzi section in Fanshi county of Shanxi province

这些缠绕状的葛万菌化石致密分布在构成核形石皮层的泥晶和微亮晶基质之中,而且在低倍显微镜下(图 7 的小矩形框所示)表现为典型的暗色致密泥晶构成

These obvious intertwisted sheath fossils of the cyanobacteria (*Girvanella*) are dense distributed in the matrix of micrites and microspars within the oncoidal cortex, and make an exhibition of composition of a dark dense micrites in low-enlarged microscope as shown in a small rectangle in Fig. 7a

物膜复杂的钙化作用产物,而且进一步表明了发生在较厚的微生物席内的多重状生物膜的钙化作用特征(Gerdes et al., 1994; Gerdes, 2010; Arp et al., 2012; Stal, 2012);核形石皮层中较高密度分布的丝状蓝细菌鞘化石构成(图 6、图 7a 和图 8),说明了建造核形石的光合作用生物膜在追求着球状聚合物的特点,应该代表着典型球状的、而且较厚的光合作用生物膜复杂的钙化作用产物,独立生长和发育在海底上而不是发生在水柱中,而且在水流作用下翻滚在细胞外聚合物质(Decho, 2010; Tourney and Ngwenya, 2014; Flemming and Wingender, 2010; Flemming et al., 2016; Decho and Gutierrez, 2017)组成的相对较厚的微生物席之中。核形石灰岩帽与鲕粒滩相邻,但是却见不到鲕粒的痕迹,表明了核形石、以及核形石灰岩帽生长和发育的相对独立性,也较为充分地表明了这一点。

因此,山西省繁峙县茶坊子剖面张夏组上部块状鲕粒滩相灰岩顶部的核形石灰岩帽,如果可以理解为核形石滩表征的“藻坪”(沙庆安和江茂生,1998)沉积的话,还可以理解为发育在鲕粒滩中的较厚的微生物席所建造的“微生物席坪”的建造物,而且在这个毯状的“微生物席坪”之中翻滚着特别的核形石。因此,核形石,由于具有双重属性,即类似于叠层石的微生物碳酸盐岩属性以及类似于鲕粒的包覆颗粒属性,所以更加明显地表征着地球历史中微生物与沉积物、乃至与流水之间极为复杂的相互作用,从而具有代表着生命与环境的长时间演变的潜力;由于要穿越成岩作用过滤器,其确切的形成机制和过程中的许多细节问题(Dupraz et al., 2009, 2011; Bosak et al., 2013),还有待于更加深入全面的研究。

5　结论

山西省繁峙县茶坊子剖面的寒武系张夏组顶部,发育和生长在高能鲕粒颗粒滩相灰岩之上的特别的核形石灰岩帽,代表着生长在高能鲕粒滩上、而且类似于“藻坪”的“微生物席毯状沉积”;所以,这一层较薄的(1 m 左右)的核形石灰岩帽,可以解释为较厚的微生物席内多重状生物膜的钙化作用产物。核形石皮层及其中的凝块、以及核形石基质中的凝块,均见到较高密度保存的丝状蓝细菌鞘化石,主要包括非缠绕状的以及缠绕状的丝状蓝细菌化石,充分说明了核形石及其相关的凝块,形成于复杂的光合作用生物膜的钙化作用。尽管针对这些核形石确切的形成机制和生长过程,还存在这许多细节问题需要进一步的研究才能得到更加合理的解释,但是,直接的微生物化石证据,表明了这些核形石形成于微生物席(或微生物膜)复杂的钙化作用和微生物沉淀作用之中。

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Particular cap oncolitic grainstones of bank oolitic grainstones
——An example from the Zhangxia Formation of the Cambrian Miaolingian at the Chafangzi Section in Fanshi County of Shanxi Province, North China

MEI Mingxiang[1,2], MUHAMMAD Riaz[1], MENG Qingfen[1], LIU Li[1]

1) *School of Earth Sciences and Natural Resources, China University of Geosciences, Beijing*, 100083;

2) *State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Beijing*, 100083

Abstract: As a particular variety of microbial carbonates, the oncoid is characteristic of double natures as following: ① the nature of the coated grain demonstrated by both the relative size and the non-smooth cortex, which common means its microbial origin and is distinct from the ooid whose origin remains uncertain; ② the nature of the stromatolite expressing as a type spherical or ellipsoid biosedimentary structure resulted from successive lamination process around the nuclei, which is a fundamental feature that is used as a basis to group the oncoid as a spherical stromatolite. One set of particular cap oncolitic grainstones of bank oolitic grainstones with the thickness of about 1 m was developed in the top part of oolitic grainstones of the carbonate bank belonging to the upper part of the Zhangxia Formation of the Cambrian Miaolingian at the Chafangzi section in Fanshi county of Shanxi procince, which represent a spectacularly sedimentological phenomenon. Many features characterize these oncoids within the cap of oncoidal limestones with the relative small thickness (about 1 m): ① the centimeter-level size (1 to 3 cm); ② the morphological feature of sphericity or ellipsoid; ③ both the dominated micritic and the secondary microspar composition of the oncoidal cortex; ④ the highly dense preservation of filamental sheath fossils of the cyanobecteria within oncoidal cortex; ⑤ a special matrix of clotted micrites with clots that are composed by filamental sheath fossils of the cyanobecteria. Although the greatest challenge that remains is the interpretation of ancient oncoids and their detail forming processes through the filter of the diagenesis, also the detail of the calcification of biofilms dominated by the cyanobacteria has still not get better understanding, the richness of direct evidence represented by microbial fossils especially for sheath fossils of the cyanobacteria within oncoids of a particular oncoidal cap in the top part of the Zhangxia Formations of the Cambrian Miaolingian in Fanshi county of Shanxi province make them become a good example of oncoids built by non-layer photosynthetic biofilms, which is an example for the further understanding of "algale flat" deposits developed on the oolitic-grained bank.

Keywords: calcified sheath fossil of the filamental cyanobacteria; oncoid; Zhangxia Formation; Cambrian Miaolingian; Chafangzi section; Fanshi county of Shanxi province

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First author: MEI Mingxiang, born in 1965, obstained his Ph.D. degree in China University of Geosciences in 1993. Now he is a professor at School of Earth Sciences and Natural Resources, China University of Geosciences (Beijing), and is engaged in sedimentology and stratigraphy. Email: meimingxiang@263.net

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