白云鄂博铁铌稀土矿床蓝细菌化石的发现及其地质意义

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摘要 白云鄂博矿床是世界著名的超大型铁铌稀土矿床, 其成因一直备受关注, 尤其是赋矿H8白云岩的成因对认识铁铌稀土成矿作用具有重要的意义. 本文报道了在西矿区块状铁铌稀土矿石中发现的微生物化石的最新研究成果. 该微生物分布于“脏”的细粒白云石中, 可能为蓝细菌丝状体, 具有直径向一端渐细的特征, 最大直径可达131 μm , 最大长度可达614 μm . 单个细胞内部结构清晰, 腔体发生了铁镁碳酸盐化, 细胞壁发生了钙碳酸盐化和硅化. 在蓝细菌白云石中可见霓石-磁铁矿白云石微碎块, 在铁铌稀土矿层可见蓝细菌化石的生物碎屑, 呈现出波动互层沉积的特点, 之后被粗粒白云石脉所充填交代. 蓝细菌的存在表明当时的水体深度较浅, 小于50 m. 以上信息指示白云鄂博矿区发育有中元古代浅海相H8沉积碳酸盐岩. 另外, 蓝细菌白云石中少量赤铁矿、磁铁矿、含铁碳酸盐和稀土矿物的存在指示沉积过程中可能有铁-稀土的初始富集.

关键词 蓝细菌, 白云石, 微生物成矿, Nb-REE-Fe, 白云鄂博, 中元古代

白云鄂博矿床是世界著名的超大型铁铌稀土矿床, 也是地质学者们“百家争鸣”之地, 基本形成了水成、火成和混合成因等认识. 铁铌稀土矿体均赋存于白云岩之中, 因此白云岩的成因是理解铁铌稀土超常富集过程的关键. 虽然火成碳酸岩成因得到了地球化学数据的广泛支持^[1-4], 但大量的野外和岩相学证据表明白云岩亦具有沉积特征, 如白云岩中微生物化石即是最直接有效的证据. 在白云鄂博周边和矿区内曾有(微)古生物化石的零星报道. 如白云鄂博群尖山组有微古植物刺球藻和球藻化石^[5], 白云鄂博以南的腮林忽洞群有三叶虫屑、疑源类、几丁虫和海绵化石^[6,7], 在主、东和西矿区的白云岩中也有微米级菌藻类、古孢子和藻类丝状体等微生物化石的报道^[8]. 但前人所报道矿区内微生物的形貌比较模糊, 并且普遍缺少微生物与白

云岩、铁铌稀土矿化之间岩相学方面的表述, 致使可信度较差.

我们在执行中国科学院地球科学研究院重点部署项目的过程中, 在白云鄂博西矿区铁铌稀土矿石的白云石中发现了大量微生物化石. 经微古生物专家初步鉴别, 属于蓝细菌. 蓝细菌是古老的生物, 为产氧光合作用的大型单细胞原核生物, 可分为单细胞和丝状体, 本次发现的主要为蓝细菌丝状体. 本文详细介绍了白云鄂博含蓝细菌化石的基本岩相学特征, 及其与铁铌稀土矿层和矿物之间的空间关系, 为白云鄂博白云岩的成因提供相关佐证.

1 矿区基本地质特征

白云鄂博铁铌稀土矿床位于内蒙古包头市以北约

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150 km处, 大地构造位置位于华北克拉通北缘. 矿床发育于中元古代白云鄂博群中, 可分为6个岩组和17个岩性段. 矿区内侵入岩主要包括中元古代火成碳酸岩、前寒武纪基性脉岩和矿区内部大面积出露的晚古生代中酸性侵入岩. 矿区内出露H1~H9岩性段, 可单独划分的东矿区、主矿区、西矿区及北矿区均赋存于白云岩中(H8), 矿体的顶板为H9和H10灰黑色板岩. H8岩性段一直以来是争议的焦点所在. 主东矿区受钠、氟交代蚀变作用强烈, Nb、稀土矿化也最为强烈. 西矿区是指主矿以西呈东西向排列的十余个小铁矿体的总称, 单个矿体呈层状、透镜状, 矿石多具条带状构造, 铁矿体与围岩界限不清, 由品位圈定. 与主东矿区相比较, 西矿区的铌、稀土矿化强度较弱, 矿石组合较为简单. 铁矿化主要以铁氧化物和碳酸岩矿物, 稀土元素主要以氟碳酸盐系列矿物和独居石等独立矿物赋存于白云岩之中. 白云鄂博成矿期复杂, 矿石类型多样, 有9种岩石类型. 其中白云石型铁铌稀土矿石主要分布在西矿, 主矿和东矿分布较少. 并且在西矿区可见到“角砾状”或“斑状”菱铁矿体, 其被细粒白云石、黑云母-磁铁矿、Nb-REE(rare earth element)矿物所交代.

2 样品一般性描述

样品采自白云鄂博西矿区西坑东侧的断面上(图1(a)), 共采集十余块矿石标本. 其中含化石样品为块状

图1 (网络版彩色)白云鄂博含蓝细菌化石样品采样位置(a)、手标本(b)及薄片照片(c, d). CF层为含蓝细菌白云石层

Figure 1 (Color online) Pictures of cyanobacteria sample location (a), hand specimen (b) and thin sections (c, d) in Bayan Obo. CF is dolomite layer including cyanobacteria

铁铌稀土矿石, 矿石局部发育白云岩脉, 具有分支复合的现象(图1(b)). 所切薄片, 一个薄片可见三小层白云岩, 每层厚约0.5~1 cm(图1(c)); 另一个薄片为单一层, 厚为0.5~1.5 cm(图1(d)). 宏观和显微镜下观察发现, 白云岩脉主要由纯净粗粒白云石组成, 并且见“脏”的细粒白云石残块和块状铁铌稀土矿残块, 显示出充填交代的特征. 蓝细菌化石分布于“脏”的细粒白云石中, 另外在块状铁铌稀土矿层之中亦发育有大量蓝细菌化石残块. 粗粒白云石“脉”主要由粗粒白云石、黄铁矿、稀土(REE)矿物、重晶石等组成; 含蓝细菌白云石残块主要由“脏”的细粒白云石、矿化蓝细菌、方解石、磁铁矿、赤铁矿、菱铁矿、黄铁矿、黄铜矿、REE矿物(主要为氟碳铈矿和含Ce氧化物)、重晶石及其他碳酸盐和硫酸盐矿物等组成. 块状铁铌稀土矿层主要由磁铁矿、霓石、细粒白云石、Nb-REE矿物、菱铁矿、赤铁矿、黄铁矿、重晶石、磷灰石等组成.

3 蓝细菌化石岩相学特征

使用Phenom XL桌面式扫描电子显微镜搭载Phenom XL能谱仪完成岩相学观察. 使用WITec 300R拉曼光谱仪进行光谱分析, 激发波长为532 nm, 光谱范围在100~4000 cm^{-1} 之间. 观察发现蓝细菌化石密集分布于“脏”的细粒白云石中, 这种“脏”可能与蓝细菌的分泌物、泥质物或矿物吸附有关. 另外, 在块状矿层中也可见少量蓝细菌化石, 但完整个体少见, 仅为生物碎屑. 化石轮廓为长柱状, 无分叉, 前端为圆柱状, 后端呈尖棱状, 具有直径向一端渐细的特征. 单体由一系列圆盘状细胞排列而成, 大小和长度不等, 最大直径可达131 μm , 最大长度可达614 μm (图2). 综合来看, 该化石的形貌与蓝细菌丝状体非常相似^[9,10]. 丝状体是由许多细胞排列而成的群体, 包括有异形胞、无异形胞及有分支的. 本文报道的可能为无分支的蓝细菌丝状体. 该类丝状体的长度和直径变化较大, 一般为几十微米, 但也有长度达数毫米, 直径数百微米丝状体的相关报道^[9,10].

显微镜下可见两种蓝细菌. 一种透光下呈黄色半透明, 内部结构清晰, 反射下表面结构不均匀, 边部为白色, 内部为黄绿色(图2(a), (b)). 另一种透光下为黑色不透明, 内部结构不清楚, 反射下整体显示均匀的黄白色(图2(c), (d)). 结合能谱分析, 初步认为前者碳酸盐化含钙更高, 后者含铁镁更高, 如部分蓝细菌发生了菱铁矿化. 在倍散射图像(BSE)下(图2(e), (f)), 蓝细菌丝状体呈现出明显的明暗变化, 内部结构清晰, 能谱显示单个

图 2 (网络版彩色)典型蓝细菌照片。黄色半透明蓝细菌与磁铁矿共生, 内部结构清晰, 反射下表面不均匀, 边部为白色, 内部为黄绿色。(a) 透射光; (b) 反射光。(c, d) 与磁铁矿共生黑色不透光蓝细菌, 内部结构不清晰(透射光)。(e, f) 蓝细菌BSE照片。(e)中蓝细菌化石赋存于富铁层颗粒间, 表现为受挤压破碎后的生物碎屑; (f)中单个细胞的内部结构清晰, 能谱显示单个细胞的细胞壁发生了钙化和硅化

Figure 2 (Color online) Images of typical cyanobacteria. Two types of cyanobacteria can be identified under transmission and reflected light: One is yellow and translucent with clear internal structure (a, b), and another is black (c, d). BSE images show that the cyanobacteria appear as the bioclasts in the ore layer (e) and the internal structure of individual cells is clear with calcification and silicification for cell wall and carbonatation for coelom (f), respectively

细胞的细胞壁发生了钙碳酸盐化, 而内部为铁镁碳酸盐化(图2(f)). 扫描电子显微镜元素扫描也显示出类似

特征(图3), 即细胞壁主要发生了钙化(图3(b)), 内部主要为Fe-Mg碳酸盐化(图3(c), (d)). 能谱和拉曼分析显示

图3 蓝细菌扫描电子显微镜图(a-e)和单质碳激光拉曼光谱图(f)

Figure 3 Scanning electron microscopic images (a-e) of cyanobacteria and laser Raman spectroscopy of carbon (f)

部分区域存在单质碳(图3(e), (f)).

4 粗粒白云石、含蓝细菌细粒白云石与块状铁铈稀土矿层之间的空间关系

初步研究认为, 含蓝细菌细粒白云石与块状铁铈稀土矿层很可能为近同时沉淀, 之后被纯净粗粒白云石脉所切割包裹. 主要依据如下: (1) 粗粒白云石填充于含蓝细菌白云石和块状铁铈稀土矿层之间(图4(a)), 而在没有粗粒白云石的区域, 两者直接接触, 各自的赋存白云石显示出明显不同的BSE灰度变化(图4(b), (c)). 含蓝细菌白云石局部可见棱角分明的Fe-Mn白云石碎块、霓石-磁铁矿碎块(图4(c)), 指示了构造充填特征. 能谱分析初步发现粗粒和细粒白云石为较纯的白云石,

块状铁铈稀土矿层中白云石为Fe-Mn白云石. (2) 块状铁铈稀土矿层局部位置有含蓝细菌白云石残块(图4(d)), 在BSE图像下两类白云石混为一体. 铈稀土磁铁矿白云石之间散布有大量的含蓝细菌生物碎屑, 完整的蓝细菌化石少见, 形貌发生了明显的扭曲变形, 多为不规则状、碎块状(图2(e), 4(d)~(g)), 显示出被块状矿体所交代残余的现象. (3) 纯净粗粒白云石中偶见蓝细菌化石, 似层状分布于含蓝细菌白云石与REE铁矿层交界的位置(图4(h)), 或在含蓝细菌细粒白云石颗粒间产出.

含蓝细菌白云石与铁铈稀土矿层为相互赋存的状态, 很可能代表着同生沉积, 互层产出于局部动荡的浅海中, 之后被纯净粗粒白云石脉所包裹残留. 需要着重指出的是, 现今看到的块状铁铈稀土矿层并不能代表

图 4 (网络版彩色)粗粒白云石、含蓝细菌白云石与块状铁铌稀土矿层三者空间关系照片。(a) 粗粒白云石填充于含蓝细菌白云石和块状铁铌稀土矿层之间(透射光)。(b, c) 含蓝细菌白云石与铁铌稀土矿层BSE图像界线截然。(c) 含蓝细菌白云石中有块状铁铌稀土矿层碎块。(d~g) 块状铁铌稀土矿层中有蓝细菌碎屑:(d~f) BSE, (g) 透射光。(h) 粗粒白云石交代细粒白云石, 其中还保留有蓝细菌化石(透射光); (i) 含蓝细菌白云石中有被磁铁矿包裹的赤铁矿核(反射光)

Figure 4 (Color online) Spatial relation photographs among coarse-grained dolomites, cyanobacteria-bearing dolomites and massive Fe-Nb REE layers. (a) Coarse-grained dolomites fill in the space between cyanobacteria-bearing dolomites and Fe-Nb REE layers (transmission light). (b, c) Boundary under BSE images is distinct between cyanobacteria-bearing dolomites and Fe-Nb REE layers. Cyanobacteria-bearing dolomites contain fragments of Fe-Nb REE layers (c), while the Fe-Nb REE layers have biotritus of cyanobacteria (d~g): (d~f) BSE images; (g) under transmission light. (h) Fine-grained dolomites are replaced by coarse-grained dolomites with sealed cyanobacteria (transmission light); (i) hematite is coated with magnetite in cyanobacteria-bearing dolomites (reflected light)

原始沉积层位的组成, 应为富铌稀土火成碳酸盐改造叠加后的结果。从含蓝细菌白云石中发育有被磁铁矿包裹的赤铁矿核(图4(i))和块状层发育有菱铁矿残晶来看, 原始沉积层位可能为含赤铁矿和菱铁矿的铁锰碳酸盐岩。

5 地质意义

5.1 H8白云岩成因探讨

虽然白云石广泛分布在古代碳酸盐台地中, 但在

现代海水中并不能沉淀白云石, 实验室在常温常压条件也不能形成结构上有序的理想白云石, 这被称为“白云石问题”^[11]。大部分学者认为白云石为高温热液次生交代成因, 但近年来的研究发现, 微生物活动和有机质参与可以形成原生白云石, 并建立了微生物白云石的概念。微生物成因白云石业已成为解决“白云石问题”的主流观点。如最近对华南陡山沱组的研究发现, 白云石可能形成于0~60°C, 沉淀于低温且微生物活跃的海水环境^[12]。本研究发现的白云鄂博白云石可能是中元古代微生物白云石的一个典型实例。

前人对白云鄂博H8白云岩和铁铌稀土矿化的成因存在严重分歧. 主要认识有: (1) H8白云岩主体为沉积成因, 稀土铌铁矿化为热液叠加改造的产物^[3,13]; (2) H8白云岩为经历过强烈结晶分异作用的侵入相碳酸岩或海相喷发碳酸岩, 与Fe-Nb-REE矿化密切相关^[1,14,15]; (3) 赋矿白云岩为大型微晶丘^[6,16]. 可见, 部分学者认为H8为沉积碳酸盐, 并遭受了后期富Nb-REE火成碳酸岩岩浆的侵入作用和流体的交代作用. 这也是绝大多数地球化学数据给出的是沉积和岩浆两者混合信息的根本原因. 因此, 要解决H8和铁铌稀土成矿的成因, 就需要寻找端元证据. 本研究在白云石中发现的蓝细菌化石显然是支持白云鄂博矿区存在沉积成因碳酸盐岩的强有力证据. 另外, 在含蓝细菌白云石中发现有少量原生赤铁矿、菱铁矿、铁白云石和稀土矿物, 表明白云鄂博H8白云岩初始主体可能为含Fe-REE的碳酸盐建造.

中元古代的白云鄂博群可能发育于与地表河流和广海相连通的潮汐潟湖相, 其海洋整体仍处于上部氧化、下部缺氧富硫的分层环境^[17]. 蓝细菌的存在使局部盆地形成富氧环境. 来自河流和洋流的Fe和REE离子交汇于该盆地中, 在蓝细菌光合作用所释放氧气的

作用下, Fe和REE可能被氧化、吸附及沉淀于生物白云石之中. 蓝细菌的生命活动可能间接控制着白云鄂博Fe-REE的迁移过程, 由此构成Fe-REE成矿的初始矿源层.

5.2 古环境的指示意义

蓝细菌是古老的生物, 在生长过程中需要进行光合作用. 一般认为其生活的水体深度小于50 m^[9], 因此白云鄂博白云石中大量蓝细菌化石的发现可以限定H8碳酸盐岩沉淀于浅海相环境. 蓝细菌放氧光合作用对古环境的改变至为重要, 使地球由无氧环境转化为有氧环境, 是海洋初级生产力的主要来源. 从白云鄂博含蓝细菌白云石矿物组成为氧化物、硫化物及碳酸盐矿物来看, 蓝细菌所释放的氧气可能主要被自身的海洋所消耗, 形成一个局部富氧的海洋环境. 另外, 海洋氧化还原条件变化对真核生物的演化和发展具有重要的促进作用. 如近同期的中元古代高于庄组泥质白云岩中不仅发育颤藻科螺旋藻宏体化石^[18], 还发育大型多细胞真核生物^[19], 表明当时的局部海洋具有较高的氧通量.

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Summary for “白云鄂博铁铌稀土矿床蓝细菌化石的发现及其地质意义”

Discovery of cyanobacteria fossils in the Bayan Obo Fe-Nb REE deposit and its geological significance

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The Bayan Obo deposit in China is known for its huge Fe-Nb-REE resource. The genesis of the ore-hosted H8 dolomite is of great significance to the understanding of the Fe-Nb-REE mineralization. Generally, there are two opposite views established: (1) Intense differentiated mantle-derived carbonates as intrusions or submarine volcanics, and (2) sedimentary origin which was metasomatized by extreme REE-enriched mantle fluids sourced from carbonatitic magmas. However, neither of them could well interpret the fuzzy information given by geochemistry and Fe-Nb-REE mineralization, hence a definite sign should be found.

This paper reports the newly discovered cyanobacteria fossils in the massive Fe-Nb-REE ores from the western ore deposit and provides detailed petrographic studies of the cyanobacteria and the spatial relationship with the Fe-Nb-REE mineralization and minerals, aiming to give a reasonable interpretation for the genesis of H8 dolomite. The samples are massive Fe-Nb-REE ores, composed mainly of microorganism dolomite fragments, massive Fe-Nb-REE layers, and coarse-grain dolomite veins. The cyanobacteria is distributed in the “dirty” fine-grained dolomites, consisting of a row of ellipsoidal cells, with a maximum diameter of ~131 μm and a length of 614 μm . The outline of the fossil is long columnar, without bifurcation, with a cylindrical front end and pointed back end. The morphology of the fossil is similar to the cyanobacterial filaments. The cell structure is clear under the BSE images, with Ca-Si mineralization for the cell wall and Fe-Mg carbonatization for the cavity. Two groups of cyanobacteria could be distinguished based on their different colors under a polarizing microscope. One group shows yellow translucent probably related with the calcite mineralization and the other group is black opacity related with the Fe-Mg carbonatization. Accessory minerals in the cyanobacteria dolomites include calcite, magnetite, hematite, pyrite, REE minerals, barite, and other carbonate and sulfate minerals.

Detailed works reveal that the cyanobacteria dolomites and massive Fe-Nb-REE layers are mutually contained and then filled by coarse-grain dolomite veins along the cracks, based on that (1) their host dolomites show very clear BSE boundary with different components, Mg-Ca vs. Fe-Mn, (2) fragments of the Fe-Nb-REE layers could be found in the cyanobacteria dolomites, while cyanobacterial bioclasts are developed in the Fe-Nb-REE layers, and (3) cyanobacteria fossils are included in coarse-grained dolomites by recrystallization of fine-grained dolomites. Therefore, the cyanobacteria dolomites and massive Fe-Nb-REE layers should be syngenetic sedimented in a locally turbulent shallow sea setting. However, we would like to point out that the massive Fe-Nb-REE layers are not the original composition of sedimentary, but the products of modification by igneous carbonatites and the original composition are most likely to be Fe-Mn carbonates.

In this paper, we tend to consider that the Bayan Obo H8 dolomite may be composed dominantly of iron-bearing carbonate formation, and is a classic case of microbial dolomite. Furthermore, photosynthesis is needed during the growth of cyanobacteria, therefore, a depth of < 50 m is the best speculation for the sedimentary of H8 dolomite. The photosynthesis of cyanobacteria was important for the alteration of the paleoenvironment. Extra oxygen produced by the microbial activity could promote the precipitation of Fe-REE minerals within the dolomite. The magmatic emplacement of Nb-REE rich carbonatites and hydrothermal fluid may have facilitated Fe deposition and contributed some iron. Therefore, the life activities of cyanobacteria may indirectly control the Fe-REE migration and mineralization process in Bayan Obo, thus forming the protore of Fe-REE mineralization.

cyanobacteria, dolomite, microbial mineralization, Nb-REE-Fe, Bayan Obo, mesoproterozoic

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