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RESEARCH ARTICLE

Calci-microbialite as a potential source rock and its geomicrobiological processes

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Abstract The calci-mircobialite is a special carbonate buildup, which is formed due to the activities of different kinds of microbes. Abundant microfossils preserved in the microbialite show the high-level productivity during deposition, while characteristic sedimentary minerals and geochemical compositions suggest an anoxic marine environment for organic burial. The high-level productivity and anoxic sedimentary environment favor the efficient preservation of organic matter and thus the formation of source rocks. On these points, microbialites could be one of the potential hydrocarbon source rocks, awaiting further geobiological investigation and exploration. Precambrian and some of the great transitional stages in Phanerozoic are critical periods when mircobialites were well developed. Widespread microbialites have been found in North and South China. Bitumen observed in many outcrops of Precambrian and late Devonian mircobialites further raises the possibility of the calci-microbialite as a potential hydrocarbon source rock.

Keywords calci-microbialite, potential source rock, geomicrobes

Geomicrobiology, proposed to be a branch of geobiology (Xie et al., 2006), mainly focuses on the investigation of ancient microbial communities concerning the types, distributions, activities, processes, evolutionary history and roles they played in the earth surface environments. Different types of microbialites, which were formed due to the life process of microbes, are often the main topic in the study of geomircrobiology. Study on ancient microbialites not only helps to recognize the evolutionary history of microbes, but also extends the knowledge about the evolutionary history and the law of the earth environments. Moreover, widespread microbialites are usually associated with the global bloom of marine microbes and the reductive environment conditions. Enhanced microbial productivity and reductive environments favor the formation of hydrocarbon source rocks. So the research on microbialites is also of economic significance for the study and prospective of oil and natural gas.

1 Calci-microbialites and the microbial activities

Burne and Moore (1987) defined microbialites as organic sedimentary deposits that have accreted as a result of a benthic microbial community (BMC) trapping and binding of detrital sediments and/or the forming of the locus of mineral precipitation. This definition emphasizes the function of BMC in the process of the microbialite formation, and indicates that microbialites are of biological or biochemical sediments. Microbialites are substantially different from calcareous algae limestone which was accumulated by abundant calcareous algae skeletons. Because most of the carbonate minerals and microfossils found in the microbialites are deposited in situ, the physical transportation by water waves is not evident. This character makes them look like a special kind of reef. However, microbialites are different from metazoan reefs in both formation mechanisms and sedimentary environments.

There are many types of microbialites, such as stromatolite, oncolite, dendrolite, thrombolite, some oolite, peloid and mudstone (Chen, 1993; Dai et al., 1996). Most microbialites are composed of carbonate minerals, and are called calci-microbialites. The calci-ooze composed of abundant planktonic foraminifers deposited on modern ocean floors does not belong to microbialites because the foraminifers are not benthic microbes.

Benthic microbial communities (BMCs) play the most important role in the formation of microbialites. According to the research on modern algal mats and microbialites, living

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BMCs are complex ecological associations of photosynthetic prokaryotes (e.g. cyanobacteria), eukaryotic microalgae, and chemoautotrophic and chemoheterotrophic microbes (e.g. sulfur bacteria). Besides these microbes, microbialites often contain some metazoans, such as small gastropods and ostracods. The complicated biochemical interactions between BMCs and associated environments result in the formation of microbialites. Microbial communities often occur by various associations/assemblages to exchange material and energy with outside environments. Liang et al. (1995) summarized the interactions between BMCs and environments into three types. The first is of the biofilm, in which BMCs inhabit and spread in detrital sediments. The second is of the mat, in which both BMCs and trapped or bound detrital sediments form a close assemblage. The last is of the induated mass, which is formed due to the mineralization of BMCs (Burne and Moore, 1987).

Interactions of microbial communities with the outside environments accelerate the recycle of material and energy, precipitation of carbonate minerals and formation of microbialites under particular conditions. Accumulation of carbonates in microbialites can be summarized into three types. The first is the physical trapping and binding of detrital sediments by microbes. The second is the biomineralization of microbes themselves (e.g. cyanobacteria calcification). The last is the abiological sedimentation, by which carbonate minerals are precipitated on the surface of organisms or sediments.

2 Distributions of calci-microbialites

Calci-macrobialites are widely distributed in the geological history, especially in Precambrian and during the great transitional stage in Phanerozoic. In Precambrian, different kinds of stromatolites were the most widely spread microbialites (Zhu, 1993). In Phanerozoic, calci-microbialites mainly occurred in Cambrian, Ordovician–Silurian (Sheehan and Harris, 2004), late Devonian (F–F) and Permian–Triassic. The reported late Devonian microbialites are characterized by *Renalcis* mound or stromatolites (Shen and Webb, 2004a, 2004b). The late Devonian microbial carbonate found in Guangxi contains abundant microfossils and could be regarded as another kind of microbialites. Currently, the Permian–Triassic microbialite has become one of the hot topics in geological study. Microbialites in that stage are widely spread in Oman (Baud et al., 1999), Armenia (Baud et al., 1997), Iran (Heydari et al., 2003), Hungary (Hips and Haas, 2006), Northern Italy (Wignall and Twitchett, 1999), Turkey (Marcoux and Baud, 1986; Baud et al., 2001, 2005), South China (Kershaw et al., 1999; Lehrmann, 1999; Lehrmann et al., 2001; Wang et al., 2005), Japan (Sano and Nakashima, 1997) and Greenland (Wignall and Twitchett, 2002). Besides stromatolites found in some sections, the P/T boundary microbialites show a special lithologic characteristic known as the graniphyric fabric structure (Fig. 1). Recently, Baud et al. (2007) summarized the research on the P/T boundary microbialites and found that they appeared not only near the P/T boundary but also throughout the early Triassic.

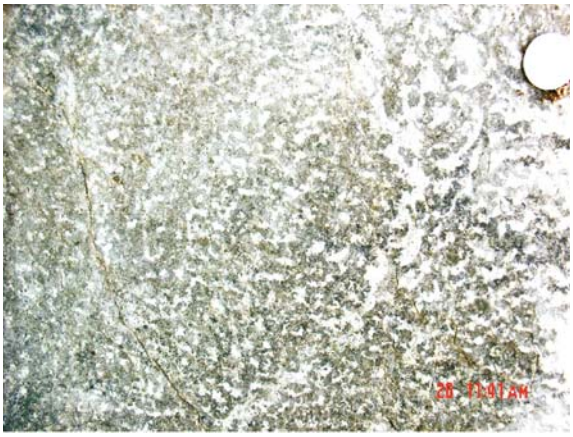

Fig. 1 Graniphyric fabric structure of the P/T boundary microbialites in Laolongdong Section, Chongqing

As one type of microbialites, modern marine stromatolites are mainly distributed in such areas as the Persian Gulf, west Australia and Florida, USA. Compared with microbialites in geological history, their distribution areas have become much more limited. Ecologically, most calci-microbialites are mainly located in shallow marine gulfs or carbonate platforms.

3 Microbial community in the microbialites

Microbes in modern marine stromatolites include photosynthetic prokaryotes (e.g. cyanobacteria), eukaryotic microalgae (e.g. brown algae, red algae and diatom), chemoautotrophic and chemoheterotrophic microbes (e.g. sulfur bacteria) and some metazoans (e.g. ostracods, Crustacea) (Konishi et al., 2001), with cyanobacteria and some anaerobic bacteria being the dominant elements. However, the microbial variety in ancient microbialites is much more difficult to determine, because most of the microbes have no calci-skeleton to be fossilized without any favorable preservation condition.

Abundant stromatolites were formed in Precambrian through the long geological history. Stromatolites are commonly considered as the integrated result of both cyanobacteria activities and sedimentation. Among the Precambrian carbonate stromatolites, well-preserved calci-microfossils were much more rare, with only some globular or setuliform fossils found in siliceous stromatolites (Zhu, 1993; Cao et al., 2003; Yan et al., 2006). This is in striking contrast with the Phanerozoic calci-microbialites characterized by the occurrence of abundant well-preserved calci-microfossils (Riding and Liang, 2005), such as cyanobacteria.

The ways to identify the microbes preserved in microbialites are usually based on the form, size, sedimentary structure (e.g. gonidial layer) and preservation conditions. Due to the similarity in the form and size, it is very hard to identify the microbes, especially the globular ones. Nowadays, organic geochemical analysis such as biomarkers provides an important means to identify some functional microbial communities in sedimentary rocks, such as cyanobacteria, green sulfur bacteria and methanotrophes (Thiel et al., 1997; Xie et al., 2005).

Some cyanobacteria can be calcified under a certain preservation condition, so they are the major microfossils which can be identified in the microbialites. The wide-spread cyanobacteria fossils are *Girvanella*, *Renalcis* and some globular species. Cyanobacteria fossils show some varieties in the geological history. For example, the structure of chambered microfossils often found in the early Triassic microbialites is similar to that of the *Renalcis*, but without any ramification.

It is worthy to point out that both the modern and the ancient microbialites have specific geographical distributions. So they are a relatively independent ecosystem. As an ecosystem, it has a special food chain, including producers, consumers and decomposers. Associated with bacteria and algae, some meztazoans with strong adaptability, such as ostracods and Crustacea, could be found in the modern stromatolites in west Australia and the Persia Gulf (Konishi et al., 2001). Comparably, in ancient microbialites, associated with cyanobacteria are mini gastropods, bivalves and ostracods; they together represent a simple but special ecosystem (Wang et al., 2005).

4 Original productivity of microbes

There are abundant bacteria and algae in modern marine stromatolites. Because of the rapid reproduction, bacteria and algae have comparable productivity with the plant system (Walter, 1994). These microfossils with the rapid reproduction were also found in ancient microbialites. For example, microfossils proposed to be the autochthonous benthic species in late Devonian and early Triassic show a very great amount (Figs. 2 and 3). The preservation of abundant microfossils implies the high-level productivity during the formation of microbialites. However, such kind of preservation is rarely observed due to the hard microbial calcification, resulting in few microfossils being found in some microbialites, such as in Precambrian stromatolites and some microbialites in early Triassic. For these kinds of microbialites with less calcified microbes being preserved, special attention should be paid to the evaluation of the original productivity. The principle of the uniformitarianism theory (known as the present is the key to the past), combined with the biogeochemical records left by microbial activities, would prevent underestimating the productivity. On the basis of the investigations conducted, the original productivity of microbialites would have been very high because their formation is related to the strong activities of a great amount of microbes.

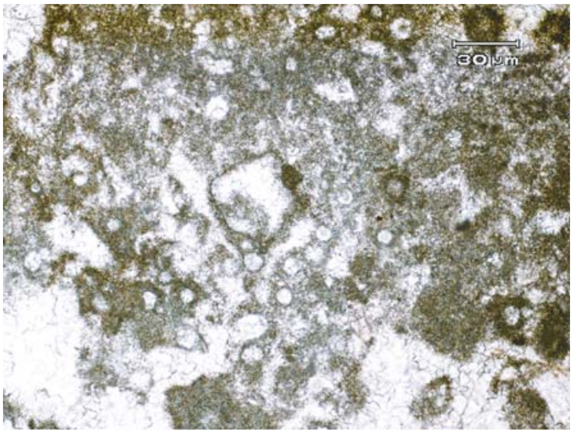

Fig. 2 Microfossils in late Devonian calci-microbialite

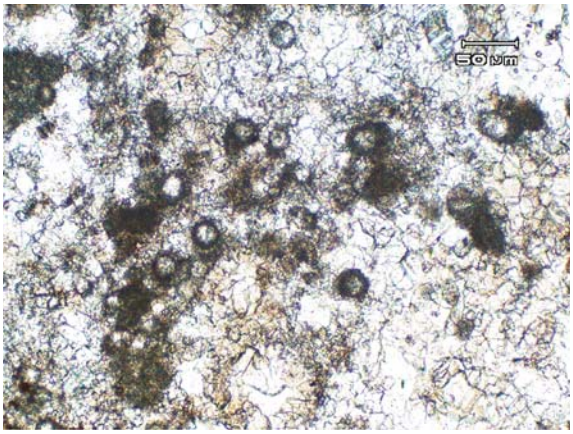

Fig. 3 Microfossils in the calci-microbialite near the Permian–Triassic boundary

5 Marine environments for the formation of microbialites and the preservation of organic matter

Although microbialites would be formed under the original high-level productivity, the amount of organic matter preserved could be changed a lot due to the oxic burial conditions and the anaerobic microbial activities during diagenesis. As mentioned above, calci-microbialites are usually built up in shallow marine carbonate platforms. The shallow marine environments usually contain much oxygen, and organic matter is easily oxidized. The difficulty in the preservation of organic matter in these environments prohibits the formation of hydrocarbon source rocks. This is a phenomenon known as higher productivity but lower preservation. It is notable, however, that the marine hydrochemical conditions or the atmospheric environments could be unusual in some particular periods, such as in Precambrian and in the great transitional stage of Phanerozoic (e.g. the T/P). This will in turn lead to the occurrence of the unusual burial conditions in the shallow marine environments, and favor the preservation of a great amount of organic matter. For example, Arnold et al. (2004) found that the Mo isotope value of Mn oxide sediments in mid-Proterozoic was 2‰ lower than that of Holocene euxinic sediments, which shows that the seafloor was anoxic for a long time during Precambrian. Marine environments were also anoxical after several mass extinctions in Phanerozoic. For example, The P/T boundary calci-microbialites, found in shallow marine carbonate platforms or on the near top of reef facies in South China, were characterized by the presence of a lot of pyrite, reflecting the reductive sedimentary environments. Wignall and Twitchett (1996) found that the Th/U values were all below 2 and that the paleocean was anoxic through the research in the geochemistry of P–Tr in north Italy, south Austria and Slovenia.

6 Possibility of microbialites as potential source rocks

The above descriptions show that some calci-microbialites would be formed under original high-level productivity, and, in some particular periods, under reductive burial conditions which favors the preservation of organic matter. On this point, it would be possible that some calci-microbialites, such as those in Precambrian or during the great transitional stage in Phanerozoic, are potential hydrocarbon source rocks.

Microbialites of different geological ages are found in a wide distribution in China, with Precambrian and the great transitional stage in Phanerozoic being the most critical periods. The Proterozoic microbialites, including stromatolites, thrombolites, oncolites, spherulites, cryptic and some bindstone (Liang et al., 1995), are widely distributed in China, covering many regions of South China, North China and Qinling fold system. In the platform of North China, Proterozoic microbialites are distributed not only in the Yanshan Mountain and Qinghe region in north Liaoning but also in the central, southern and western areas of North China platform, e.g. the Zhongtiao Mountain, Taihang Mountain, Xiaoqinling, Ordos, Helan Mountain and Yinshan Mountain (Zhu, 1993; Liang et al., 1984; Qiu et al., 1992).

Liang et al. (1993) also found abundant microbialites in Bayan Obo Group in the regions from Bayan Obo to Siwangziqi in the northernwest North China platform. Bayan Obo Group, in which many mini-stromatolites were found, is similar to the Gaoyuzhuang Formation and Wumishan Formation (Middle Proterozoic) of Yanshan Mountain in lithology, sedimentary facies and stromatolites.

According to the data of Liang et al. (1995), if the west and the east of the northern margin of the North China platform were uniformly located in the similar epicontinental sea, the length of the microbialite belt from the west to the east would extend about 1 000 km, and the width from the north to the south could be 100–200 km. In addition to the northern margin, if the western and the southern margin of the North China platform belonged to an uniform sedimentary basin, there would be another microbialite belt extending in length from the north to the south by 500–600 km and in width from the west to the east by 300–400 km. The microbialites in the above regions of the North China platform are distributed widely, with the thickness ranging from 500–600 to over 1 000 m, and even approaching to 3 000–5 000 m in the regions from Kuancheng to Jixian County in east Yanshan Mountain. The huge thickness has exceeded that of any marine Phanerozoic strata developed in the North China platform (Liang et al., 1995).

During the long time of Precambrian, the earth environments are considered to be anoxic, and at the same time the bacteria and algae bloomed, so good-quality hydrocarbon source rocks may be formed even in the epicontinental sea. Many oil seepages were found in the bitumen limestone in Gaoyuzhuang Formation and Wumishan Formation of Mesoproterozoic, in which mini stromatolites were developed. Some researchers considered these as good-quality source rocks (Liang et al., 1995).

The late Devonian and Permian–Triassic are the most important transitional periods in Phanerozoic, during which microbialite were found to be well developed. In Nanpanjiang in South China, calci-microbialites formed by bacteria and algae in late Devonian are widely distributed with great

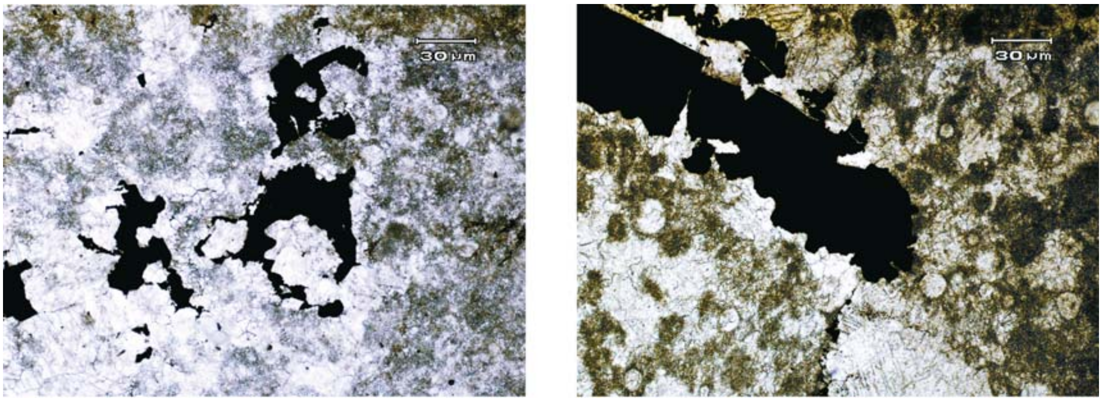

Fig. 4 Remained bitumen found in the late Devonian microbialites in Guangxi

thickness. The P/T boundary microbialites are distributed much more widely, including the regions of Nanpanjiang area, East Sichuan, Chongqing, and low–middle reach of the Yangtze River, but with a thin thickness ranging from several meters to more than ten meters.

Residue bitumen was found to occur in late Devonian microbialites in Guangxi (Fig. 4). The microbialites near the Permian–Triassic boundary display strong fluoresce indicative of the presence of organics, which could be compared to the microbial carbonate in the hypersaline lake of Bahamas (Dupraz et al., 2004).

To sum up, the calci-microbialites occurred in a variety of geological ages in South and North China. The microbialites were distributed widely and usually with a great thickness, implying that they are probably a particular kind of carbonate source rock worthy of further study. Microbialites are served not only as a kind of source rocks but also as the reservoir rocks (Liang et al., 1995). Although calci-microbialites have the advantage to form carbonate source rocks, the types, preservation and occurrence of organic matter in the microbialites awaits further investigations.

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