

Review of molar tooth structure research

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Abstract For more than a century, molar tooth structure (MTS) has been studied. The study developed in three stages. During the first stage (before 1980), researchers described three basic morphologies of MTS, mainly from the Belt Supergroup in North America, and they provided several hypotheses for the origin of MTS. During the second stage (1980–1999), the frequent discoveries of MTS on all continents resulted in many detailed descriptions of their shape and in several hypotheses concerning the origin of MTS. Notably, hypotheses of MTS's origin such as seismic activity and biological activity were developed. Since 2000, research has progressed into a new stage (the third stage). This is due to discoveries of MTS in the Mesoproterozoic of China and elsewhere, and the ongoing debate on the seismic or biological origin is replaced by a hypothesis that involves gas expansion and chemically-controlled carbonate precipitation (both of them possibly affected by biological activities). This latter idea has gradually been commonly recognized as the mainstream theory. Despite continued disagreements, researchers now agree that microsparry calcite played a controlling role regarding the development and the global distribution of MTS in time and space during the Proterozoic, the morphological diversity, and the impact on the sedimentary environment. The present contribution analyses the three major hypotheses regarding the origin of MTS; it also discusses the shortcomings of the hypotheses regarding a seismic or biologic origin, and it details the modern hypothesis that links formation of cracks to the precipitation of sparry calcite. It is deduced that important questions dealing with the Precambrian can be answered, among other aspects regarding the depositional palaeogeography and stratigraphic correlations.

Key words molar tooth structure, sparry calcite, Precambrian

1 Introduction

Since Bauerman (1885) first introduced the term “molar tooth (MT)”, more than 300 papers have been published to discuss this special sedimentary structure that only developed in the Proterozoic carbonate rocks. Examination of 336 papers related to molar tooth structure (MTS) indicated that MTS studies represent at least three main stages.

During the first stage (before 1980), researchers not only focused on the morphology of MTS, including the

vertical and horizontal sheet-like features and the pod-like shape (O'Connor, 1972; Horodyski, 1976), but also discussed the origin of MTS, particularly of those found in the Mesoproterozoic (1.47–1.1 Ga) of the Belt Supergroup in North America. Three potential origins for MTS were recognized that (1) MTS might have resulted from cleavage of lithified rock due to shear forces, and thus would be secondary in nature (Daly, 1912; Fenton and Fenton, 1937; Rezak, 1957); (2) similarly to the stromatolites, MTS was created by algae and represented an in-situ biological-origin structure (Ross, 1959; Plfug, 1968; Smith, 1968; O'Connor, 1972); and (3) MTS resulted from multiple origins, such as sheet MTS formed by organisms

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directly, and podlike MTS originating from other activity of organisms (*e.g.* the decayed organic materials producing air bubbles) (Horodyski, 1976). Thus, people can imagine that these ideas marked the beginning of disputes on the origin of MTS.

During the second stage of MTS investigation (1980–1999), additional discoveries of MTS were reported, including examples from the Neoproterozoic of North America (James *et al.*, 1998), Norway (Knoll, 1984), Spain (Braga *et al.*, 1995), West Africa (Bertrand-Sarfati and Moussine-Pouchkine, 1988; Moussine-Pouchkine and Bertrand-Sarfati, 1997), Australia (Calver and Bailie, 1990), and India (Sarkar and Bose, 1992), as well as Meso–Neoproterozoic of Siberia (Petrov, 1993; Bartley *et al.*, 1997) (Table 1). In addition, during this period, MTS was recognized in China for the first time (Fairchild *et al.*, 1997). Moreover, with regards to the origin of MTS, several influential theories emerged, including the origins related to seismic activity (Pratt, 1992, 1998, 1999; Qiao *et al.*, 1994), and the widespread gas expansion hypothesis that considered how air bubbles played the role to create MTS (Frank and Lyons, 1998; Furniss *et al.*, 1998). Because of the frequent discoveries of MTS in both Meso- and Neoproterozoic strata, the shapes of MTS became even more diverse and complicated, leading to more intricate and varied interpretations of origin.

During the third stage of MTS investigation (since 2000), many researchers turned attention to China. Professor Meng, the leader of the International Geoscience Program (IGCP) 447 (2001–2005, titled of “*Microsparry (Molar-Tooth) Carbonates and the Evolution of the Earth in the Proterozoic*”), greatly promoted the MTS study. These investigations were built upon MTS and related lithologic discoveries during the 1980s; for example, in the northern part of Jiangsu and the Anhui provinces, where MTS was referred to as either abnormal calcite veins or the calligraphy-like structure (Jiangsu Geology and Mineral Exploration Bureau, 1984); in Jilin Province, where it was called the vermicular limestone (Jilin Geology and Mineral Exploration Bureau, 1988); and in Liaoning, Shandong, and Jiangsu Provinces, where they were called mesh-like calcite veins or calcareous veinlets (Liaoning Geology and Mineral Exploration Bureau, 1989). During this period, additional MTSs were discovered in the Meso- and Neoproterozoic across China. These Chinese MTS sites are located in Jilin, Liaoning, Jiangsu, Anhui, Shandong, Henan and Yunnan Provinces, Xinjiang and Inner Mongolia (Qiao *et al.*, 1994, 2001; Qiao and Gao, 1999; Du *et al.*, 2001; Meng and Ge, 2002; Liu *et al.*, 2003;

Jia *et al.*, 2003; Kuang, 2003; Gao and Liu, 2005; Liu *et al.*, 2005). Subsequent to the reports of MTS discovery in the Neoproterozoic in the northeastern, northwestern and southwestern China and North China, MTS was also described from the Mesoproterozoic Gaoyuzhuang Formation in the Jixian region (Mei, 2005), Tianjing of North China and Wumishan Formation in the western Liaoning Province (Kuang *et al.*, 2009b, 2012; Meng *et al.*, 2011). In addition to Chinese occurrences, MTS was continually recognized in the Meso- and Neoproterozoic around the world in Siberia (Bartley *et al.*, 2000; Petrov and Semikhatov, 2001; Pope *et al.*, 2003), Russia and the East European Platform (Bartley *et al.*, 2007; Kah *et al.*, 2007), India (Chaudhuri, 2003), Norway (Melezhik *et al.*, 2002), Greenland (Fairchild *et al.*, 2000), West Africa (Gilleaudeau and Kah, 2010), and South Africa (Bishop and Sumner, 2006).

During the third stage, MTS has also been discussed in broader terms, than simply its mode of origin, although the discussions of origin reached the unprecedented levels, particularly with respect to, the seismic origins (represented by Qiao) and the biological origin (represented by Meng and the expansion of understanding combined origins of MTS and its microsparry infill (Bishop and Sumner, 2006; Bishop *et al.*, 2006; Pollock *et al.*, 2006; Long, 2007; Kuang *et al.*, 2011b; Hazen *et al.*, 2013). Additional researches have included investigation of composition, texture, geochemistry morphology, and potential origin of microsparry calcite within MTS (Crawford and Kah, 2004; Crawford *et al.*, 2006; Bishop *et al.*, 2006; Pollock *et al.*, 2006; Bartley and Kah, 2007; Goodman and Kah, 2007), and depositional environments (Stagner *et al.*, 2004; Gilleaudeau and Kah, 2010). Much of this work has only been published in abstract form.

Recently, there are only a few published papers regarding the MTS study from outside of China. During the period of 2000–2014, among more than 230 papers related to MTS, there are 130 papers involving Chinese MTS research approximately (Table 1 and Figure 1). Moreover, the theme of concern is no longer the origin of MTS oftentimes, but using it as a symbol of subtidal facies or as a specific facies useful for geochemical analysis (Bartley *et al.*, 2007; Kah *et al.*, 2007; Petrov, 2011; Bose *et al.*, 2012; Hoffman *et al.*, 2012; Kah *et al.*, 2012). Eventually, the upsurge of MTS research just comes to China in the recent decades.

We are left with a series of questions: What is MTS? And what characteristics does it have? Why is it of so frequent debates? Why researchers cannot reach a consensus after

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