Palaeogeography, Palaeoclimatology, Palaeoecology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Current molded, storm damaged, sinuous columnar stromatolites: Mesoproterozoic of northern China

Fabio Tosti, Robert Riding *

Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN 37830, USA

A R T I C L E I N F O

Article history:
Received 1 April 2016
Received in revised form 8 October 2016
Accepted 12 October 2016
Available online xxxx

Keywords:
Mesoproterozoic
North China
Sinuous
Stromatolite
Heliotropism
Tieling

A B S T R A C T

A thin (~50 cm) horizon of sinuous stromatolites occurs within a succession of elongate upright columns in the ~1.4 Ga Tieling Formation, near Jixian, China. The upright columns form aligned closely spaced ridges, separated by narrow runnels with signs of current scour. The sinuous and upright stromatolites, and their intervening matrix, were originally mainly composed of carbonate mud. In end-on view, the sinuous columns incline back and forth. Each column consists of well-defined laminae that successively rotate relative to column curvature, maintaining their orientation approximately at right-angles to the column axis. In inclined parts of the columns, laminae are typically asymmetric and the steeper side faces the direction of column inclination. We interpret this column sinuosity to be a response to changes in current-direction, with accreting laminae facing into currents that supplied sediment. We find no evidence for heliotropism (mat growth towards the sun) in these examples. Adjacent columns typically show similar shapes, bending back and forth together, but their angles of curvature and inclination can change laterally from column to column, from near vertical to 45°, over distances of 30 cm. Columns can show breakage and separation of adjacent laminae. Some of this is enhanced by compaction and stress, but the occurrence of sinuous columns on their sides or upturned, in spaces between undisturbed columns, indicates that column curvature developed during growth and that toppling of columns was syndepositional. We infer that sinuosity developed in response to changes in current direction, that column inclination reflects current strength, and that breakage and toppling was produced by strong currents. Curved and sinuous columns could reflect shoaling. This would also have exposed them to storm damage and to the effects of currents that scoured sufficient matrix to locally break and topple columns. Markedly sinuous Mesoproterozoic columns also occur in Siberia and North America, suggesting that similar conditions and processes of stromatolite formation may have been widespread at this time. Formation and preservation of the sinuous stromatolites described here required a combination of conditions that included abundant fine-grained carbonate sediment, microbial mats capable of trapping it, reduced early lithification, and absence of bioturbation.

1. Introduction

Columnar stromatolites that are common in the mid-late Proterozoic (~1600–600 Ma) exhibit a wide variety of shapes (Cloud and Semikhatov, 1969; Raaben, 1969; Awramik, 1971; Raaben et al., 2001). This morphological diversity mainly involves column width and branching style, but also includes whether columns and branches are upright or inclined (Hofmann, 1973). It is not uncommon for columns to be slightly curved (Cloud and Semikhatov, 1969), and stromatolites that are gently sinusoidal in vertical section have attracted attention from suggestions that their growth may have been heliotropic, and could therefore reflect seasonal or latitudinal changes in the relative position of the sun (Vanyo and Awramik, 1982, 1985). Qu et al. (2004) assumed that the growth of sinuous stromatolites in the ~1.4 Ga Tieling Formation of northern China was controlled by the direction of solar radiation, and proceeded to calculate the paleo-obliquity of the ecliptic. However, this and other interpretations of heliotropism in sinuous Proterozoic stromatolites have been questioned (Williams et al., 2007). Stromatolite columns analyzed for heliotropism are generally gently flexuous, with large angles of curvature typically >130°. However, some curved columns show much more marked changes in column inclination (e.g., Fenton and Fenton, 1937, fig. 14a). Exceptionally, they change direction several times, curving back and forth at angles of 90° or less (Serebryakov, 1976, fig. 1). The origins of stromatolites with sinuous columns, and especially those with marked low angle changes in direction, remain poorly understood. In contrast, inclined columns, which are much more common than sinuous forms, have often been attributed to current effects (Rezak, 1957, p. 148; Hoffman, 1967, fig. 3; Hofmann, 1973; Eagan and Liddell, 1997), including columns that face in opposing directions in successive beds (Horodyski, 1989, p. 27 and fig. 4).

* Corresponding author.
E-mail address: rriding@utk.edu (R. Riding).

http://dx.doi.org/10.1016/j.palaeo.2016.10.019
0031-0182/© 2016 Published by Elsevier B.V.

Here we explore the possibility that marked sinuosity in ~1.4 Ga stromatolites, in the Tieling Formation of northern China, was produced by, and changed with, directed water flow (Tosti and Riding, 2015). The sinuosity of these Tieling examples, with up to three sharp curves, is locally enhanced by compaction, but sinuous columns that lie on their sides between upright columns indicate primary sinuosity and synsedimentary displacement, which we attribute to currents and storms. We propose that the primary mode of accretion of these sinuous columns, as in upright columns in the same succession (Tosti and Riding, in press), was trapping of current-supplied fine carbonate sediment, and that the laminae (and therefore the columns) grew into the current, i.e., towards the source of the sediment. As current direction changed, so did the direction of growth. This style of directional accretion, termed *clastitropism* by Shapiro et al. (1995), is observed in present-day agglutinated columns such as Lee Stocking Island (Dill et al., 1986; Shapiro et al., 1995), although the sediment trapped by these Bahamian examples is generally much coarser than at Tieling. We do not rule out other factors influencing sinuous column development elsewhere, but we propose that these markedly flexuous Tieling examples reflect the effects of change in direction of current-supplied sediment on the growth of agglutinated columns.

2. Geological setting

The sinuous stromatolites described here occur in the middle of the ~1.4 Ga Laohuding Member (upper Tieling Formation), at Tieling village near Jixian city, ~90 km east of Beijing.

2.1. Jixian section

About 100 km east of Beijing, a ~9.5 km thick succession of Proterozoic sedimentary rocks is exposed over a distance of ~20 km, between the Great Wall and Jixian city. This is the classic 'Jixian Section' of North China (Gao et al., 1934; Kao et al., 1934, fig. 4; Chen et al., 1980, 1981; Cao and Yuan, 2003, pp. 7–11; Shi et al., 2014) (Fig. 1). This relatively well-preserved succession is divisible into two parts. The lower part is latest Paleoproterozoic and early Mesoproterozoic (~1650–1320 Ma) and consists of the Changcheng Group (Changzhougou, Chuanlinggou, Tuanshanzi, Dahongyu formations), Jixian Group (Gaoyuzhuang, Yangzhuang, Wumishan, Hongshuizhuang, Tieling formations), and Xiamaling Formation. The upper part is the early Neoproterozoic (~1000–800 Ma) Qingbaikou Group (Changlongshan and Jingeryu formations) (Su et al., 2010, fig. 6). These ages are based on SHRIMP dates (Gao et al., 2007, 2008; Lu et al., 2008; Li et al., 2009, 2010; Su et al., 2008, 2010; Li et al., 2013, tables 1,2). Previously, the Changzhougou-Xiamaling succession as a whole was regarded as ~1800–950 Ma, and the Jixian Group (with the Tieling Formation at its top) as ~1400–1000 Ma (Chen et al., 1981; Lu, 1992). The newer dates therefore indicate that the Tieling Formation is ~1.4 Ga rather than ~1.0 Ga in age.

2.2. Tieling Formation

The Tieling Formation, at the top of the ~1650–1400 Ma Changcheng-Jixian succession (Li et al., 2013), occurs widely throughout the Yanshan Mountains west, north and east of Beijing (Qu et al., 2014, fig. 6). We studied the Tieling Formation in its type area in the southernmost part of the Jixian Section, ~5 km north of Jixian (Gao et al., 1934; Kao et al., 1934, p. 248). In this area, Chen et al. (1980) subdivided the Formation into the lower Daizhuangzi Member (153 m of sandstone, shale, manganiferous dolostone, limestone and thin stromatolite bioherms), and the upper Laohuding Member (180 m of manganiferous dolomite and dolomitic limestone overlain by a thick stromatolitic unit and then dolomitic limestone) (see Su et al., 2010, p. 3313) (Fig. 2). Based on zircons in a bentonite in the middle part of the formation, the Tieling Formation is dated 1439 ± 14 Ma at Dayu Shan, 4 km south of Tieling village (Li et al., 2014). Su et al. (2010) estimated the age of the top of the Tieling Formation as ~1.4 Ga. We therefore regard the Laohuding Member as ~1439–1400 Ma (late Calymmian). The thin sinuous stromatolite horizon described here occurs in the lower part of the Stromatolite Unit of the Laohuding Member (Tosti and Riding, in press) (Fig. 2). We examined it at the Old Quarry Section (40° 5′17.27″N, 117°23′48.69″E) in 'Tieling Geopark', 300 m ENE of Nantaoyuan village (Fig. 3).

The Stromatolite Unit is ~77 m thick. Its lower part is well-exposed in the Old Quarry Section, where it is dominated by thick planar bedded stacked units of columnar elongate ridged stromatolites (Tosti and Riding, in press). End-on, these are seen as upright columns with

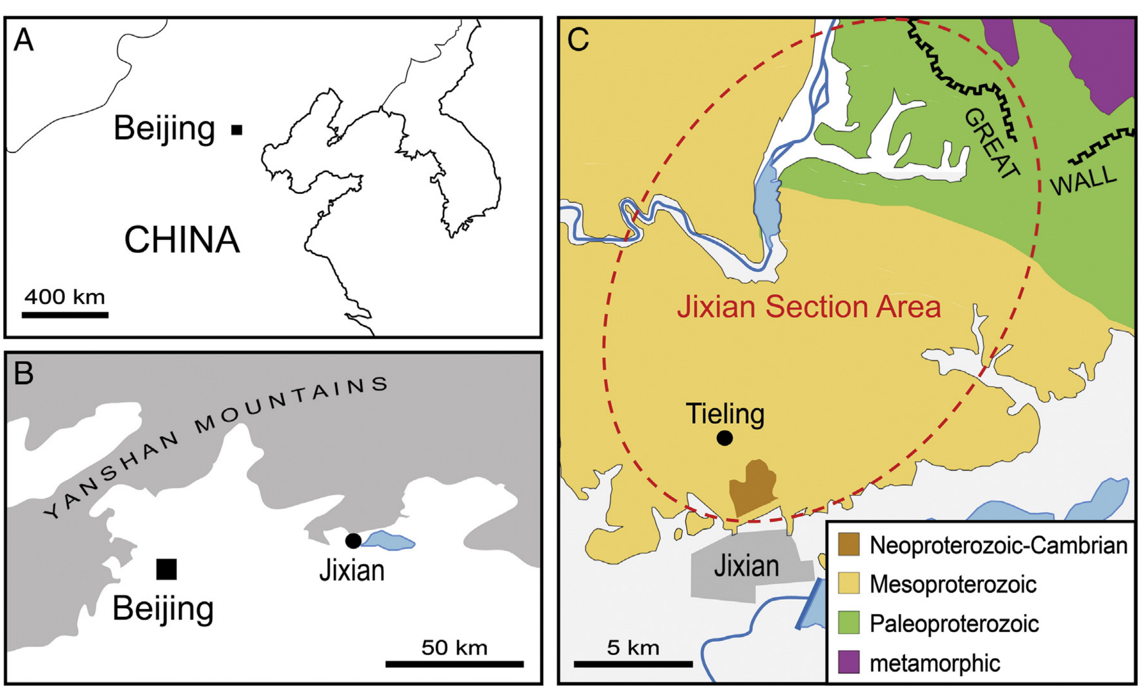

Fig. 1. Location of Tieling village and the area of the 'Jixian Section' of Proterozoic sediments, 100 km east of Beijing, China.

Please cite this article as: Tosti, F., Riding, R., Current molded, storm damaged, sinuous columnar stromatolites: Mesoproterozoic of northern China, Palaeogeogr. Palaeoclimatol. Palaeoecol. (2016), http://dx.doi.org/10.1016/j.palaeo.2016.10.019