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

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ABSTRACT

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).

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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

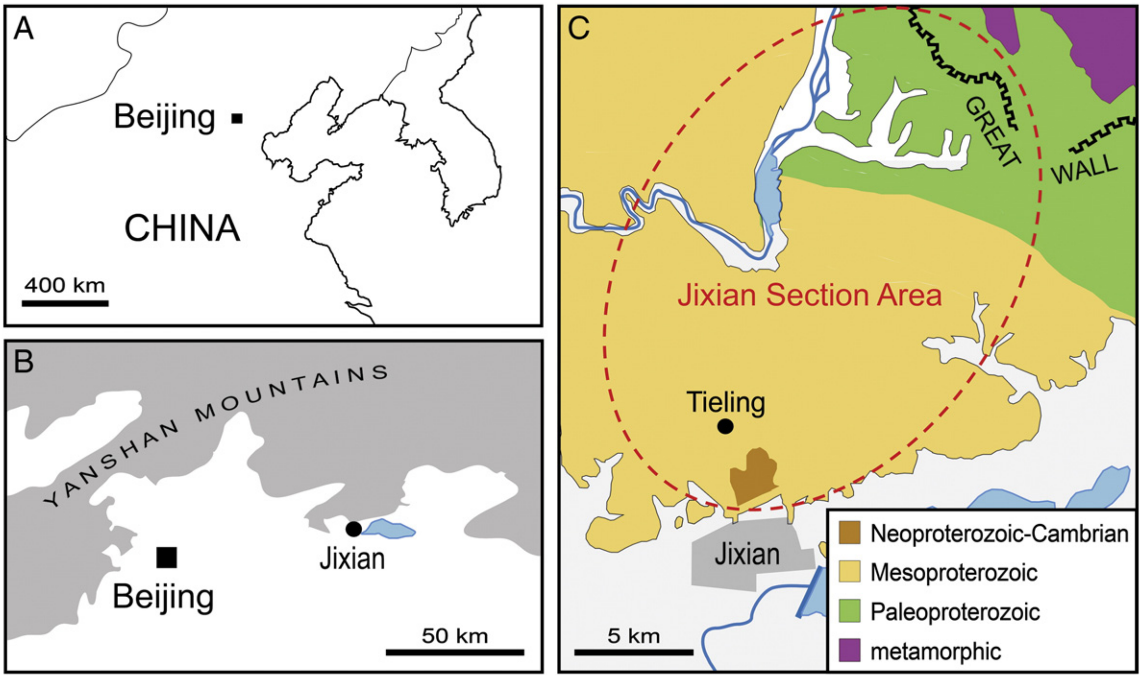

Fig. 1. Location of Tieling village and the area of the 'Jixian Section' of Proterozoic sediments, 100 km east of Beijing, China.

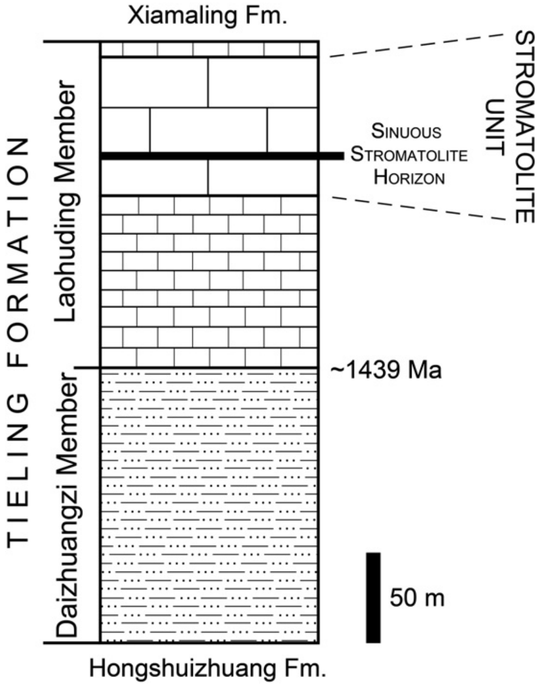

Fig. 2. Stratigraphic log of the Tieling Formation in its type-area (Chen et al., 1980) near Tieling village, 5 km north of Jixian city. The sinuous stromatolite horizon described here is in the lower part of the Stromatolite Unit (Tosti and Riding, in press), which in turn is in the upper part of the Laohuding Member. The mid-Tieling Formation is dated ~1439 Ma (Li et al., 2014).

frequent branching, separated by narrow erosional runnels. Columns and matrix primarily consist of fine-grained carbonate with occasional small intraclastic flakes (Tosti and Riding, in press). Their well-defined laminae commonly show truncation. These columns are interpreted as fine-grained agglutinated stromatolites that formed in a current-swept environment where there was abundant carbonate mud (Tosti and Riding, in press). At the Old Quarry Section, the sinuous stromatolites described here occur as two thin layers that form a ~50 cm horizon within this succession of vertical columns (Fig. 4). They show signs of synsedimentary damage, including toppling and breakage.

3. Sinuous stromatolites

Columnar stromatolites with curved axes have been described as *sinusoidal* (Vanyo and Awramik, 1982, 1985) and *S-shaped* (Qu et al., 2004). Here we propose the term *sinuous stromatolite* to describe columns that end-on, in vertical section, are variously flexuous, from gently curved and sinuous to L-, S- or *Z*-shaped. Sinuous stromatolites can branch, and the columns may be either rounded or elongate in plan, as shown by examples of *Platella* (Serebryakov, 1976, fig. 1; Raaben et al., 2001, fig. 49).

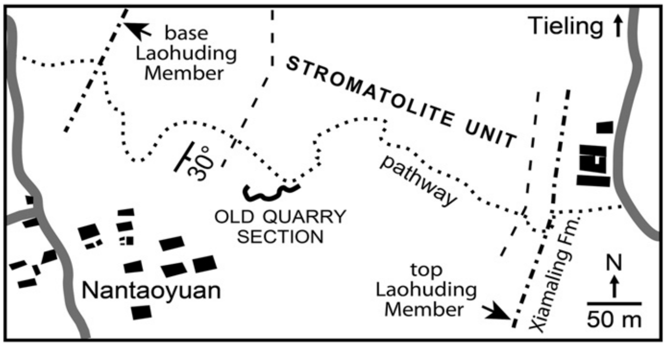

Fig. 3. Outcrop map of the Laohuding Member at Tieling Geopark, 0.5 km SSW of Tieling village. The Geopark extends east along a pathway from the Old Quarry Section to the base of the Xiamaling Formation, near the road south of Tieling. The sinuous stromatolites described here occur in the lower part of the Stromatolite Unit, and are exposed in the Old Quarry Section.

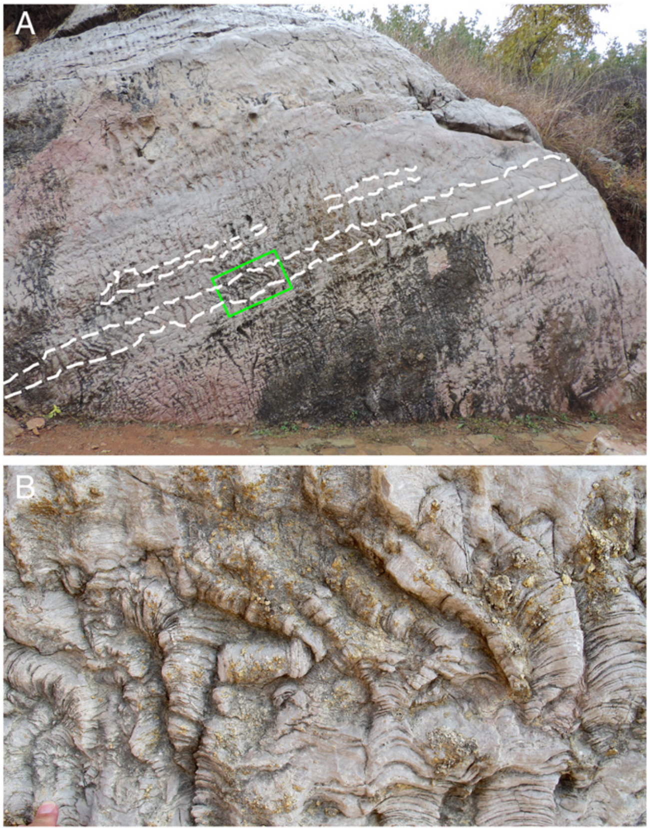

Fig. 4. Sinuous stromatolite horizon in the Laohuding Member, Old Quarry Section, Tieling Geopark. A. View facing south showing the two thin units (outlined) that comprise the sinuous stromatolite horizon, within a succession of upright, often branched, and undisturbed elongate columns. The thicker (~17 cm) lower unit is more laterally persistent than the thinner upper (~15 cm) unit, and they are separated by ~18 cm of upright columns. Width of view ~7 m. B. Detail of the lower unit (box area in A) showing a broken column (left center) toppled sideways between upright (left) and steeply sloping (right) columns. Note both sinuosity and branching in the narrow columns immediately to the right of the toppled fragment. Width of view 50 cm.

3.1. Succession and morphology

The lower part of the Stromatolite Unit of the Laohuding Member (Fig. 2) exposed in the Old Quarry Section at Tieling Geopark (Fig. 3) is dominated by upright branched stromatolites, which in plan view are elongate (Tosti and Riding, in press). Two layers of sinuous columns within this succession of elongate branched erect columns form a 50 cm horizon. The columns include C-shaped and S-shaped forms, some of which are broken and displaced. The lower (17 cm) sinuous layer is more even and laterally persistent than the upper (15 cm) layer, and they are separated by an 18 cm layer of upright columns (Fig. 4A). Both of the sinuous horizons locally include upright columns, some of which branch (Fig. 5A). Occasionally, sinuous columns also branch (Fig. 6A). The sinuous columns range in width from ~1–7 cm and, in common with upright columns in the associated succession, their laminae show low synoptic relief, ~1–2 cm. Laterally, over short distances (~30 cm), the slopes of these sinuous columns can change by up to ~45°. The curved and sinuous columns can be closely juxtaposed, with only very minor amounts of intervening matrix (Fig. 5B), but there are also instances where they are separated by relatively narrow matrix-filled interspaces (Fig. 6B, C) similar to those that typically

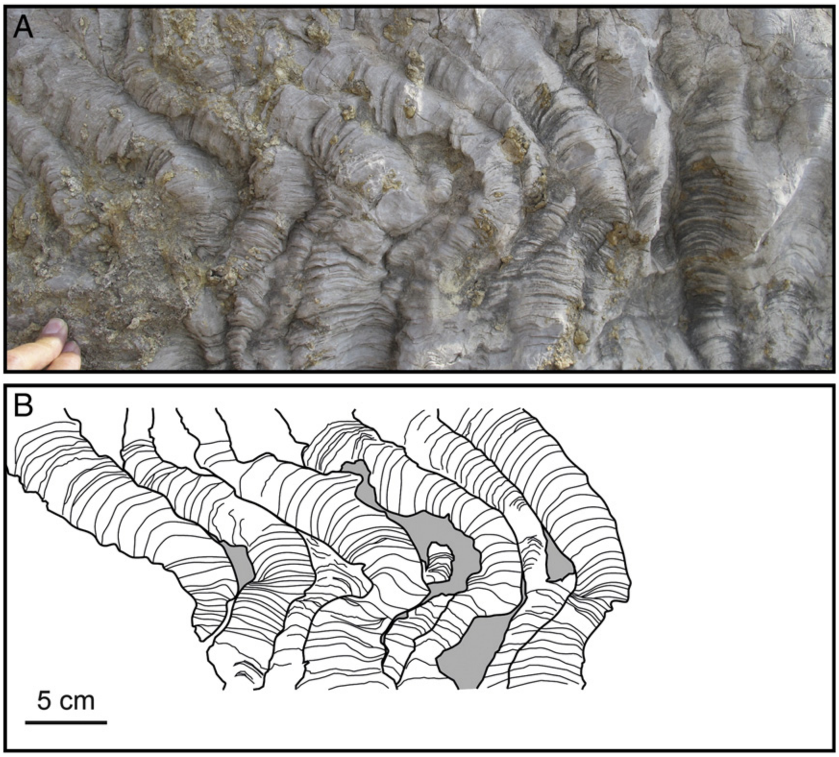

Fig. 5. Sinuous stromatolite horizon, Laohuding Member, Old Quarry Section, Tieling Geopark. A. Columns showing variation in sinuosity and increase in curvature to the left. Note upright branched column to right, and overlying stylolitic truncation. B. Tracing of column outlines and laminae, with inter-column matrix shown in gray.

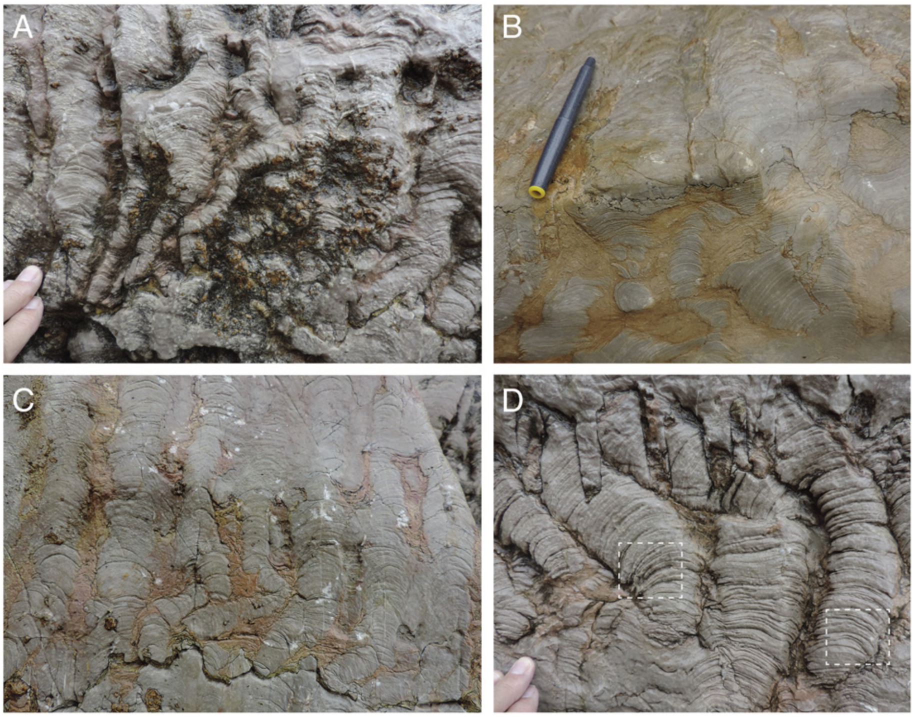

Fig. 6. Sinuous stromatolite horizon, Laohuding Member, Old Quarry Section, Tieling Geopark. A. Upright, sloping, curved and sinuous columns, one of which is conspicuously branched. B. Oblique view of columns that are curved and sinuous in vertical section (lower part of photograph) and elongate (parallel to pen) in plan (upper part of photograph). Red-brown matrix separates the gray colored columns. In the vertical (lower) section, some of the columns are seen to be partly separated. Maximum pen width is 1 cm. C. Upright, curved and sinuous columns, most of which are separated by narrow red-brown matrix-filled interspaces. Upright columns (left and right) are separated by two sinuous columns (center of photograph) with angular bends that show separation and dislocation along laminae. Sinuous columns adjacent to upright columns suggests the sinuosity was original, and that dislocation and breakage was synsedimentary and/or due to later compaction and stress. Width of view 30 cm. D. Adjacent columns show changes in lamina orientation and shape with column orientation. In upright parts of columns, laminae are more symmetrically convex, whereas sloping columns tend to have asymmetric laminae that are steeper in the direction of column inclination (white boxes) (Fig. 7). See also Fenton and Fenton (1937, Fig. 9b). Note stylolite cutting column tops.

separate upright columns in the immediately underlying and overlying succession (Tosti and Riding, in press). The top surfaces of beds show that curved and sinuous columns are laterally elongate (Fig. 6B), similar to branched upright columns in the sequence. However, due to outcrop limitations, elongation in sinuous columns has not been seen to exceed ~25 cm, and it has not been possible to determine whether displaced sinuous columns are also laterally elongate; some might be rounded in plan.

3.2. Curvature and lamination

Both curved and upright stromatolites show well-defined laminae. In sinuous columns, the laminae appear to track column curvature; maintaining angles approximately normal to the column axis (Fig. 6D). In the vertical parts of columns, the laminae are convex up. As the column progressively curves to left or right, lamina orientation rotates and in steeply sloping columns the laminae become sub-vertical. In addition to these changes in lamina orientation with curvature, lamina shape also appears to alter, from symmetrical in upright columns to asymmetrical in inclined columns. As a result of this asymmetry, which can be angular, one side of the lamina slopes more steeply than the other (Fig. 6D). Thus, whereas vertical columns tend to have symmetric laminae (Fig. 7A), inclined columns have asymmetric laminae and, in general, the side of the lamina in the direction of column inclination is the steeper one, irrespective of whether it is the longer or shorter side (Fig. 7B). Similar examples can be seen in sinuous Altyn stromatolites of the Belt-Purcell Supergroup (Fenton and Fenton, 1937, pl. 9, fig. 2). Successive laminae therefore track the inclination of the column axis, and also change in symmetry in response to column inclination.

3.3. Displacement

Broken and displaced columns, especially small ones, are locally conspicuous within the sinuous horizon. Breakage tends to occur between laminae, especially where column curvature was greatest. It ranges from partial separation (Fig. 6B), to column dislocation and complete mutual separation (Fig. 6C). In more extreme cases, displaced columns occur on their side between adjacent in place columns (Figs. 4B, 8). Locally, sinuous stromatolite horizons are strongly stylolitized (Fig. 6D).

4. Interpretation

The upright columns that dominate the succession below and above the sinuous horizon in the Old Quarry section, are fine-grained, contain current truncated laminae, and accreted beside narrow runnels occupied by similar fine-grained carbonate together with small micritic flake-like intraclasts (Tosti and Riding, in press). We interpret these upright columns to have been created by bacterial mats that trapped allochthonous carbonate mud and silt in a current-swept environment, and that the columns were initially cohesive but not rigidly lithified (Tosti and Riding, in press). We infer a broadly similar trapping origin and cohesive state for the sinuous columns. So how did their curved and sinuous shapes develop, alongside as well as between upright columns, and how did they come to be locally toppled and broken while upright columns did not? We suggest these effects could have been due to changing current flow conditions and storm damage in shallow shoal conditions that not only produced curved and sinuous columns but at times subjected them to breakage and displacement. There is, however, also evidence for post-burial breakage.

Fig. 8. Small curved and sinuous columns displaced between large relatively upright columns. This juxtaposition suggests that both sinuosity and displacement were syndepositional. We interpret this as storm/current damage that locally broke and displaced cohesive columns, and that probably involved scour removal of sufficient intervening matrix to cause columns to break and fall (Fig. 11). Sinuous stromatolite horizon, Laohuding Member, Old Quarry Section, Tieling Geopark.

4.1. Current effects on lamina accretion and column shape

As noted above, in addition to tracking changes in column inclination, successive laminae tend to be asymmetric in inclined columns, with the steeper side generally facing the direction of column inclination (Figs. 6D, 7B). This asymmetry is evidence that column curvature is primary, and not produced by post-depositional deformation of upright columns. The relationships between column inclination, lamina shape and orientation suggest that laminae grew into currents, i.e.,

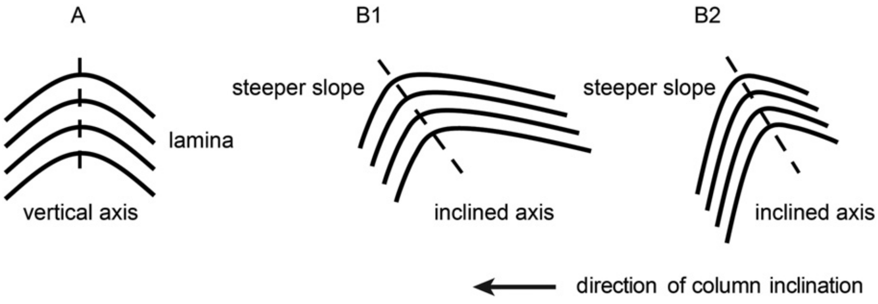

Fig. 7. Diagrammatic illustration of changes in lamina shape with column inclination between upright and sinuous stromatolites. A. In upright columns, laminae tend to be symmetrical. B. In inclined columns, laminae tend to be asymmetrical. Either the shorter (B1) or the longer (B2) lamina side can face the direction of column inclination. However, in both cases, the side facing the direction of column inclination tends to be the steeper one (Fig. 6D). See also Fenton and Fenton (1937, Fig. 9b).

towards the source of sediment, and that as current direction changed, so did the direction of accretion (Fig. 9). This would explain why the laminae of inclined columns tend to be angular, and why the steeper face – in the direction of column inclination – faces 'up-current'). This polarity appears to be irrespective of whether the steeper face is the longer or shorter one (Fig. 7B). It contrasts with cross-bedding and dune migration, where the lee slope (slipface) is steep, and erosion truncates the tops of laminae on the upcurrent (stoss) side (Fig. 10). Since mats can stabilize (trap and bind) grains as they arrive, laminae tend to accrete towards the current. Mat agglutination therefore creates lamina geometries distinct from those of mobile bed-forms.

Thus, we interpret curved and sinuous Tieling columns as products of sediment accretion by mats, primarily in response to changes in current direction. The columns were built by laminae that accreted towards the sediment source. Column inclination therefore reflects sustained and relatively strong current direction. With weaker currents, column axes tend to be more vertical. As current direction changed, so did the direction (and therefore slope) of column accretion. In addition, difference in degree of column slope reflects difference in current strength; weaker currents resulted in less column inclination than stronger currents (Fig. 9). We therefore conclude that column sinuosity can reflect current strength as well as current direction. Based on this interpretation, that sinuous and curved stromatolite Tieling columns reflect sediment accretion in response to changes in current direction, they could be classed as clastitropic (Shapiro et al., 1995), which also suggests 'high-velocity currents' (Shapiro, 2007).

4.2. Split, broken and displaced columns

These curved and sinuous columns often show varying degrees of deformation and breakage, and it is important to distinguish early (syndepositional) and later (compactional, structural) effects. We infer that the columns were cohesive but probably not rigidly lithified. This is consistent with evidence of incomplete synsedimentary lithification in the upright columns of the associated succession that show scour, and also with bent, plastically deformed, platy flat pebble conglomerate clasts higher and lower in the Laohuding succession (Tosti and Riding, in press). If so, and the columns were initially cohesive rather than rigid, it is conceivable that initially upright columns were synsedimentarily deformed into curved and sinuous shapes. Two observations lead us to reject this as a general explanation for these sinuous columns. First, curved and sinuous columns occur, both in place (Fig. 6A) and displaced (Fig. 8), alongside and between erect columns. Secondly, lamina symmetry appears to change with column curvature (Fig. 6D). We therefore conclude that column curvature in these examples was essentially primary. However, there are also signs that original curvature and sinuosity has been affected by post-depositional compactional and structural effects. Examples include partial separation of columns along laminae, as well as column dislocation, especially near angles of curvature (Fig. 6C). We have not observed damage among the upright stromatolite columns that dominate the immediately underlying and overlying beds. It therefore seems that column irregularity, including syndepositional breakage, in the sinuous horizons created a zone of weakness within a more competent succession. This could also have localized stylolite formation (Fig. 6D). Nonetheless, we do not envisage that compaction could account for overturned columns (some of which are sinuous) between undisturbed columns (Fig. 8).

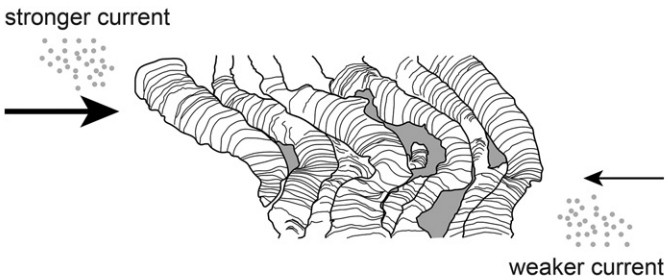

Fig. 9. Interpretation of lamina development in curved and sinuous columns (based on Fig. 5B). Laminae accreted into the oncoming current, i.e., towards the supply of sediment (clastitropism). As current direction changed, so did the direction of accretion. In addition, as current strength increased so did the angle of column inclination. Thus, the degree of column slope reflects is directly related to current strength, with weaker currents (lower right) producing less column inclination than stronger currents (upper left).

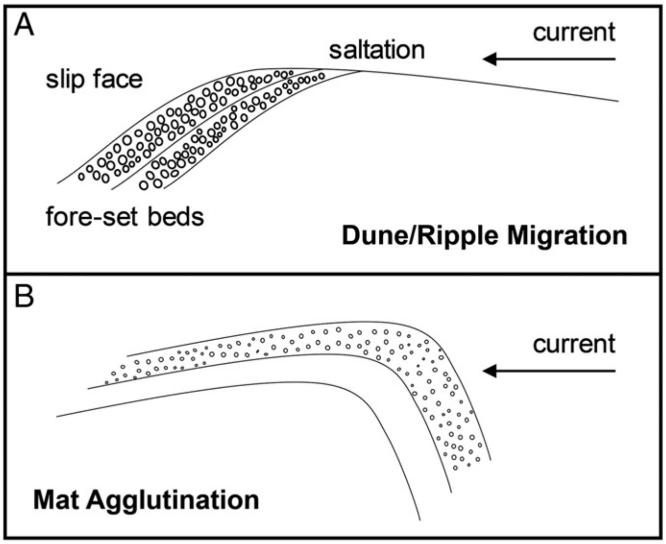

Fig. 10. Agglutinated mat accretion contrasted with dune bedding. A. In dune/ripple migration, grains migrate in the current direction and accumulate as fore-set beds on the down-current slip face. B. In agglutinated mat accretion, grains are trapped and bound on the mat surface. Thus, grains can accumulate over the entire mat, but also (in contrast to dunes) preferentially accumulate on the up-current mat surface. As a result, mat laminae are laterally extensive but also thicker and often steeper up-current.

4.3. Synthesis of column accretion, current effects, toppling and breakage: shoaling, variable currents, and storm effects

We propose that these two thin horizons of inclined, curved and sinuous columns with asymmetric laminae, reflect localized shoaling within a succession of otherwise upright columns. Shallowing in response to sediment accumulation patterns could increase variability in current flow direction, as in present day sand and mud shoals in both siliciclastic and carbonate environments (Dyer and Huntley, 1999; Rankey et al., 2006; Coco and Murray, 2007; Holland and Elmore, 2008; Reeder and Rankey, 2009; Syvitski et al., 2010; Harris et al., 2011). Such dynamic change in shallow environments might not only create fluctuations in column accretion direction as currents switched, but also lead to deep scouring of inter-column runnels that created column instability and local collapse. This would account for co-occurrence of curved to sinuous forms and broken and displaced columns. In addition, or alternatively, runnel scour and column damage could reflect storm effects exacerbated by shoaling. We suggest the following possible sequence of events: 1. Columns accreted sinuously in response to changing current directions, 2. Inter-column runnels were locally excavated by strong scour that exposed previously buried columns. 3. Some columns broken by this process toppled into partially excavated runnels (Fig. 11). Breakage preferentially affected smaller columns which now occur displaced between larger undisturbed columns (Figs. 4B, 8).

5. Discussion

Directional growth in stromatolites can be a response to a variety of factors (Shapiro, 2007), e.g., heliotropism (Nordeng, 1959),

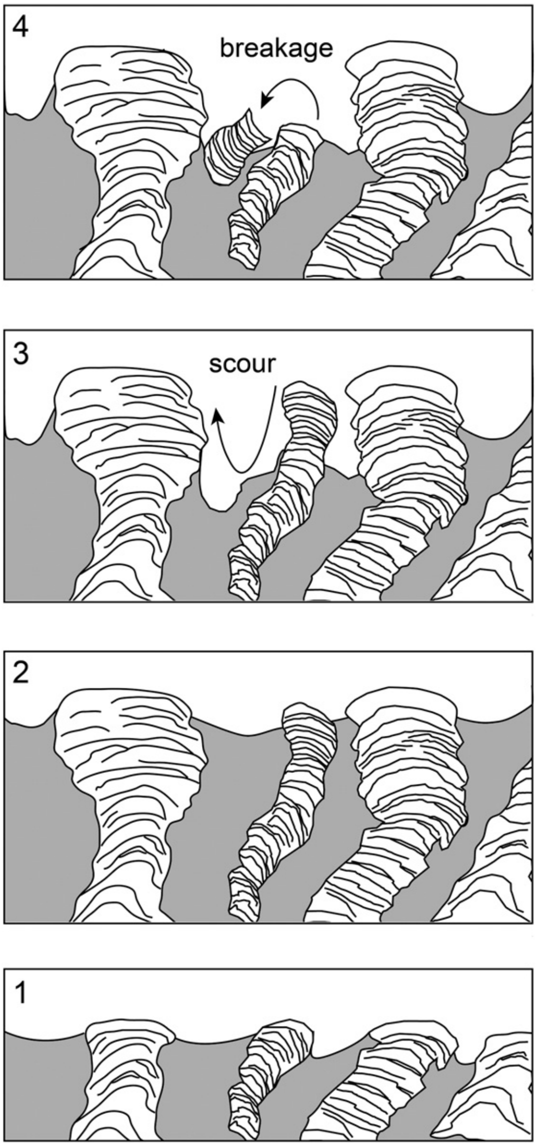

Fig. 11. Inferred sequence of events leading to localized breakage and displacement of cohesive columns by current/storm effects. 1–2. Columns accrete sinuously in response to changes in current direction. 3. Scour excavates inter-column runnel, exposing previously buried column margins. 4. Upper part of a column is broken by currents and toppled into the partially excavated adjacent runnel. Breakage preferentially affected narrow (weaker) columns which now occur displaced between larger undisturbed columns (Figs. 4B, 8).

chemotropism (Greinert et al., 2002), and gravitropism (Shapiro, 2005). Shapiro (2007) noted that 'in high-velocity currents, the stromatolites may accrete into the current'. This is observed, for example, in present-day Lee Stocking columns that 'lean' towards the incoming tidal flow (Dill et al., 1986) and which Shapiro et al. (1995) regarded as clastitropism (growth towards the source of clastic sediment in agglutinated stromatolites). Although sinuosity has been attributed to heliotropism in a few examples, inclined and curved stromatolites have, in general, much more widely been regarded as products of current action (Hofmann, 1973, and see below).

5.1. Other curved and sinuous examples

Platella, from the 1272–1211 Ma (Gorokhov et al., 2006) Debengda Formation of the Olenek Uplift, northern Siberia (Serebryakov, 1976, fig. 1), shows elongation that resembles the ridge-runnel system of upright columns at Tieling, but its flexuous columns are much taller than the sinuous columns described here. It is not clear whether inclined *Platella*-like stromatolites in the late Neoproterozoic of British Columbia are sinuous in vertical or plan view (Hofmann and Mountjoy, 2001). Curved Proterozoic stromatolites on Socheong Island, South Korea, resemble some Tieling sinuous examples, but are evidently structurally deformed and their primary morphology remains unclear (Kong and Lee, 2013). Sinuous forms that closely resemble Tieling examples in shape and size, and are similar in age, occur in the Altyn Formation of the ~1400 Ma Belt-Purcell Supergroup, Montana (Fenton and Fenton, 1937, pl. 9; Horodyski, 1983, fig. 4b; Horodyski, 1989, fig. 3c), and also in the Helena/Siyeh (Fenton and Fenton, 1937, pl. 18, fig. 1; Horodyski, 1977, fig. 4b; Horodyski, 1983, figs. 13e, 15a). Fenton and Fenton (1937), pl. 9, fig. 2) described sinuous Altyn forms as having grown 'without crowding'. Horodyski (1989), p. 27 and fig. 4b) inferred that they probably reflect the effects of both currents and slumping. However, other Belt sinusoids appear undeformed, and are also elongate (Fenton and Fenton, 1937, fig. 14, and p. 1941; Horodyski, 1989, fig. 3c). In addition, sinuous Belt-Purcell columns are inclined in opposite directions in successive beds (Horodyski (1989), fig. 4b). This supports our view that currents are a more likely cause of inclination in these types of stromatolite than heliotropism (see Section 5.3. Heliotropism, below). We are not aware of Phanerozoic examples of sinuous columns, but large (15–30 cm wide) curved columns in the Cambrian (~500 Ma) of Utah have been attributed to current effects by Eagan and Liddell (1997), p. 294, fig. 11.6b), who noted that this interpretation is 'consistent with other paleocurrent data'. Columns inclined in opposing directions in the Gillespie Lake Group (Delaney, 1981), part of the Wernecke Supergroup (<1.64 Ga, Furlanetto et al., 2013), do not appear to be sinuous.

5.2. Inclined columns

Whereas distinctly sinuous columns are relatively rare, there are numerous records of columns inclined in only one direction. Inclination in present-day stromatolites at both Shark Bay and Yellowstone has been attributed to heliotropism (Awramik and Vanyo, 1986), although it has also been noted that Shark Bay columns incline seaward (Hofmann, 1973, fig. 6) 'into the oncoming waves' (Hoffman, 1976, p. 270), and Dill et al. (1986) observed that Lee Stocking columns lean towards the incoming tide, suggesting clastitropism (Shapiro et al., 1995). Preferential accretion towards currents was described by Hoffman (1967), fig. 3) in ~1.9 Ga Pethei stromatolites. In an even older example, small obliquely oriented, laterally linked stromatolite columns could reflect current influence in ~2800 Ma Steep Rock Lake carbonates (Fralick and Riding, 2015, p. 141). Inclined *Conophyton* in the Helena/Siyeh of the 1.47–1.4 Ga Belt-Purcell has also been attributed to current action (Rezak, 1957, p. 148; Horodyski, 1983, fig. 13a, p. 418), as have Altyn stromatolites inclined at 45 degrees (Horodyski, 1976, fig. 4c; Horodyski, 1983, fig. 5, p. 397). In describing inclined and curved Altyn columns, Horodyski (1989), p. 27 and fig. 4b) noted that 'the inclination is an original growth attribute and not a feature caused by soft-sediment deformation', but added 'However, where separated by a substantial distance, some slumping may have occurred'. Belt-Purcell columns appear to be much more commonly inclined than Tieling examples. Examples in the Altyn (e.g., Horodyski, 1983, fig. 4b, 5d–e) include columns inclined in different directions in subsequent beds (Horodyski, 1976, fig. 5c). Significantly, inclination can be a marginal feature of stromatolite bioherms. Young and Long (1976), figs. 2 and 5) show that elongate ~900–1000 Ma (van Acken et al., 2013) *Inzeria* columns lean outward at angles of ~25° on mound margins, and Serebryakov (1976), fig. 3) shows similar inclinations at the margin of a *Baicalia* bioherm in the Neruen Formation (~1025 Ma, Anisimova et al., 2012) of Uchur-Maya, Siberia). Horodyski (1977), fig. 3) attributed similar arrangement in ~1.4 Ga Belt-Purcell to columns perpendicular to convex bioherm surfaces. However, we have not observed bioherms at Tieling, and the Tieling units with upright columns are planar (Tosti and Riding, in press).

5.3. Heliotropism

Heliotropism, organic movement or growth towards sunlight, has been reported in present-day stromatolites (Awramik and Vanyo, 1986; Vanyo et al., 1986), and inclined stromatolite columns of Proterozoic age have been used to calculate paleolatitude (Nordeng, 1959, 1963; Vologdin, 1961, 1963; Kusky and Vanyo, 1991), although Fedorchuk et al. (2016) observed no evidence of a phototropic response to incident light in the specimens studied by Nordeng (1963). However, since column inclination could also reflect current effects (Rezak, 1957; Hofmann, 1973), it has been suggested that heliotropism in stromatolites could more confidently be inferred from column sinuosity, i.e., a sine wave growth pattern, in which case it might also indicate day-length and days per year, as well obliquity of the ecliptic (Vanyo and Awramik, 1982, 1985). Kusky and Vanyo (1991) plotted column inclinations for Mesoproterozoic Belt-Purcell stromatolites, but noted that they might have been affected by currents. In a study of S-shaped Tieling stromatolites near Zhoukoudian, ~50 km SW of Beijing, Qu et al. (2004), figs. 4, 5) estimated paleo-obliquity of the ecliptic, as well as days/year, days/month, and hours/day from the thicknesses of the light-dark lamina pairs. On the basis of stromatolite morphology, Kim and Kim (1999) correlated stromatolitic carbonates on Socheong Island, South Korea, with the Qingbaikou System in China which, in the Jixian area is represented by Xiamaling and younger Proterozoic units above the Tieling Formation. Some Socheong stromatolite columns resemble sinuous and curved forms at Tieling. Kong and Lee (2013) did not exclude the possibility that Proterozoic Socheong stromatolites in South Korea might be heliotropic, but considered that their shape could better be interpreted as secondary structural deformation. Australian *Anabaria* columns interpreted as heliotropic by Vanyo and Awramik (1982, 1985) are gently flexuous (rather than S-shaped), and were originally thought to belong to the ~850 Ma Bitter Springs Formation. However, Williams et al. (2007) regarded them as younger (~600 Ma) *Kotuikania* and considered the column sinuosity to be a 'fortuitous product of column irregularity and column branching to accommodate adjacent columns'. Williams et al. (2007) also criticized the results of Qu et al. (2004), and suggested that strong branching with common divergence and convergence of columns is morphologically incompatible with heliotropic growth.

A heliotropic origin seems unlikely in our Tieling sinuous forms for at least three reasons. First, the great majority of columnar stromatolites at Tieling lack sinuosity, and it is difficult to invoke heliotropism only to account for the thin horizons in which curved and sinuous columns are conspicuous within this thick succession of generally vertically elongate stromatolites. Second, curvature in Tieling columns often tends to be abrupt rather than sine-form in shape, although post-depositional compaction could be involved in this. Third, even within these thin horizons, column curvature changes significantly over short distances (e.g., 30 cm), and curved and upright columns can occur side-by-side (Fig. 5A). Thus, overall and in contrast with the suggestion of Qu et al. (2004), we find no convincing evidence for heliotropism in sinuous Tieling columns.

5.4. Environmental and secular and significance

The elongate sinuous stromatolites of the ~1.44–1.40 Ga Laohuding Member are strikingly similar to coeval ~1.47–1.4 Ga examples in the Belt-Purcell Supergroup of Laurentia (Fenton and Fenton, 1937; Horodyski, 1977, 1983, 1989). Larger, but also broadly similar, *Platella* in the Debengda Formation of northern Siberia (Serebryakov, 1976) is dated 1.272–1.211 Ga (Gorokhov et al., 2006). It is possible that mid-Mesoproterozoic development of these sinuous stromatolites reflects particular sedimentary and biological conditions. These could include, but not be limited to, (i) intense carbonate mud precipitation that simultaneously lessened early lithification, e.g., 'whiting' events (Knoll and Swett, 1990; Grotzinger and Knoll, 1999) driven by cyanobacterial CO_2-concentrating mechanisms (Riding, 2006), (ii) growth of weakly lithified cohesive agglutinating microbial mats (Seong-Joo and Golubic, 1998) that could trap this sediment and were very responsive to moderately strong multi-directional current-activity, (iii) absence of synsedimentary processes, such as grazing and bioturbation, capable of disturbing/destroying these deposits as they formed (Garrett, 1970). Such concurrent and time-limited conditions favoring formation of these distinctive stromatolites could also account for their relative scarcity. This concept that specific, 'Goldilocks', requirements promoted development of these sinuous stromatolites should be explored and refined. Fine-grained agglutinated stromatolites that remained weakly lithified prior to burial may be scarcer than is generally thought. Further studies could shed light both on this and on their precise stratigraphic distribution.

6. Conclusions

1. Tieling sinuous stromatolites occupy a relatively thin bed within a succession of upright branched columns. Columns show rapid lateral change in sinuosity and inclination, and can range from upright to steeply inclined over distances of 30 cm. Some sinuous columns show irregular branching, and most are elongate in plan.
2. These curved and sinuous columns reflect dynamic interaction between mat growth and fine-grained current-supplied sediment. We attribute column sinuosity to change in current direction. Mat surfaces trapped carbonate mud and preferentially accreted up-current towards the source of sediment supply. Fluctuations in current direction and strength over time caused laminae, and thus columns, to rotate as they tracked these periodic changes. As lamina orientation changed with current direction, so did column shape, generating curved to sinuous columns with up to three prominent bends.
3. Local scouring of narrow matrix-filled spaces between adjacent stromatolite columns by strong - possibly storm - currents excavated and weakened columns, some of which broke and toppled onto their sides. These displaced columns are generally small, and were presumably weaker. Variations in current direction and strength that created column sinuosity may have developed in response to sediment shoaling. This also would have made columns prone to episodic scour and damage, as currents removed sufficient matrix to break and topple some columns.
4. There is evidence of compactional dislocation and breakage of sinuous columns. However, horizontal displaced columns between upright in place columns show that syndepositional breakage and displacement also occurred, and we attribute this to current scour. We infer that this horizon of initially sinuous and locally broken columns created a zone of weakness within a more competent succession, and localized later compaction and stress. Locally this caused additional column breakage as well as stylolite formation.
5. These sinuous columns are generally elongate, as are upright branched stromatolites in the under- and overlying succession. However, elongation of the sinuous columns appears to be relatively short, and some columns may be ovoid or rounded in plan.
6. We find no evidence of heliotropism (mat growth towards the sun) in these sinuous columns, and several features seem to specifically preclude it here. These include: restriction of sinuous columns to a thin horizon between successions dominated by upright stromatolites, the presence of laterally adjacent upright columns, lateral change in the degree of sinuosity over short distances, and sinuosity that tends to be angular rather than sine-form.
7. Tieling sinuous columns show close similarities to mid-Mesoproterozoic examples in Laurentia (Belt-Purcell Supergroup, 1470–1400 Ma) and Siberia (Olenek, 1272–1211 Ma). This might suggest concurrent development of abundant fine-grained carbonate

sediment, microbial mats capable of trapping it, reduced early lithification, and absence of synsedimentary processes (e.g., bioturbation) capable of destroying these stromatolites as they formed. Secular limitation of these particular conditions could also account for the apparent scarcity of sinuous columns at other times.

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