SOLAR CYCLICITY IN THE PRECAMBRIAN MICROFOSSIL RECORD

by ZHANG ZHONGYING

ABSTRACT. The first detailed investigation of a probable noctidiurnal growth rhythm of the tubular oscillatoriacean cyanophyte *Siphonophycus inornatum* Y. Zhang, in stratiform stromatolites of the mid-Proterozoic Gaoyuzhuang Formation (*c.* 1400–1500 ma), Hebei Province, North China, is presented herein. The sequence consists of light, thick, silica-filled layers alternating with dark, thinner, algal-rich layers. The filaments exhibit a distinct, layered pattern of horizontally orientated populations alternating with vertically orientated populations. The light layers are composed of erect filaments and are interpreted as recording phototactic, daytime algal growth; the dark layers are composed of prostrate filaments and reflect nocturnal growth. This layered, cryptalgal microfabric is quite similar to the noctidiurnal growth patterns of *Phormidium hendersonii* Howe filaments in modern stromatolites from the Caribbean area. In favourable conditions the daily increments recorded by fossil biolamination doublets reached as high as 600–700 μm. Such biolamination confirms a solar cyclicity 1400–1500 ma ago.

STROMATOLITES, both fossil and Recent, are interpreted by most workers as organosedimentary structures produced by sediment trapping, binding, and/or precipitation resulting from metabolic activity and growth of organisms, primarily blue-green algae (Awramik *et al.* 1976). Recent stromatolites have been described from several areas of modern carbonate sedimentation, including Shark Bay, Western Australia, the Persian Gulf, the Bahamas, Bermuda, and the Great Salt Lake, Utah. Fossil stromatolites were widespread, particularly in the Precambrian, and reached a high abundance and diversity by mid- to late Precambrian. They have been used for environmental and palaeoecological analyses, and for time-stratigraphic correlation of ancient sediments. To assess the usefulness of stromatolites, however, it is essential to determine the potential effect of both environmental and microbial factors on stromatolite growth. Studies of the microbiology and morphogenesis of Recent stromatolites provide a basis for the interpretation of Precambrian stromatolites. Such comparisons are especially valuable in deciphering the mode of formation of Precambrian stromatolites.

In 1983 I made a reconnaissance of the *c.* 1400–1500 ma old Gaoyuzhuang Formation (Changchengian System) of Pangjiabu, Zhangjiakou, Hebei Province, North China (text-fig. 1); rock samples were collected from black cherts of stratiform stromatolites at different horizons within the formation. A preliminary note (Zhang and Li 1984) reported the discovery of a probable noctidiurnal growth rhythm of a filamentous cyanophyte, using petrographic thin sections cut perpendicular to the lamination. This paper formally describes and illustrates the rhythmic growth, movement, and particle-trapping behaviour of the micro-organism that built the stromatolites. Their potential significance as environmental and palaeoecological indicators is also discussed.

GEOLOGICAL SETTING AND AGE

The Precambrian geology and stratigraphy of the Western Yanshan Range, Hebei Province, have been discussed in detail by Du and Li (1980). In the Pangjiabu region, about 115 km north-west of Beijing (Peking), Hebei Province, a 1500 m thick section of essentially unmetamorphosed Changchengian (mid-Proterozoic) sedimentary rocks is well exposed (text-figs. 1 and 2). The Changchengian System rests unconformably upon the Archaean Qianxi Group (dated as over 3000 ma to *c.* 3600 ma by K–Ar, Rb–Sr isochron, and U–Pb isochron determinations: Cheng *et al.* 1982)

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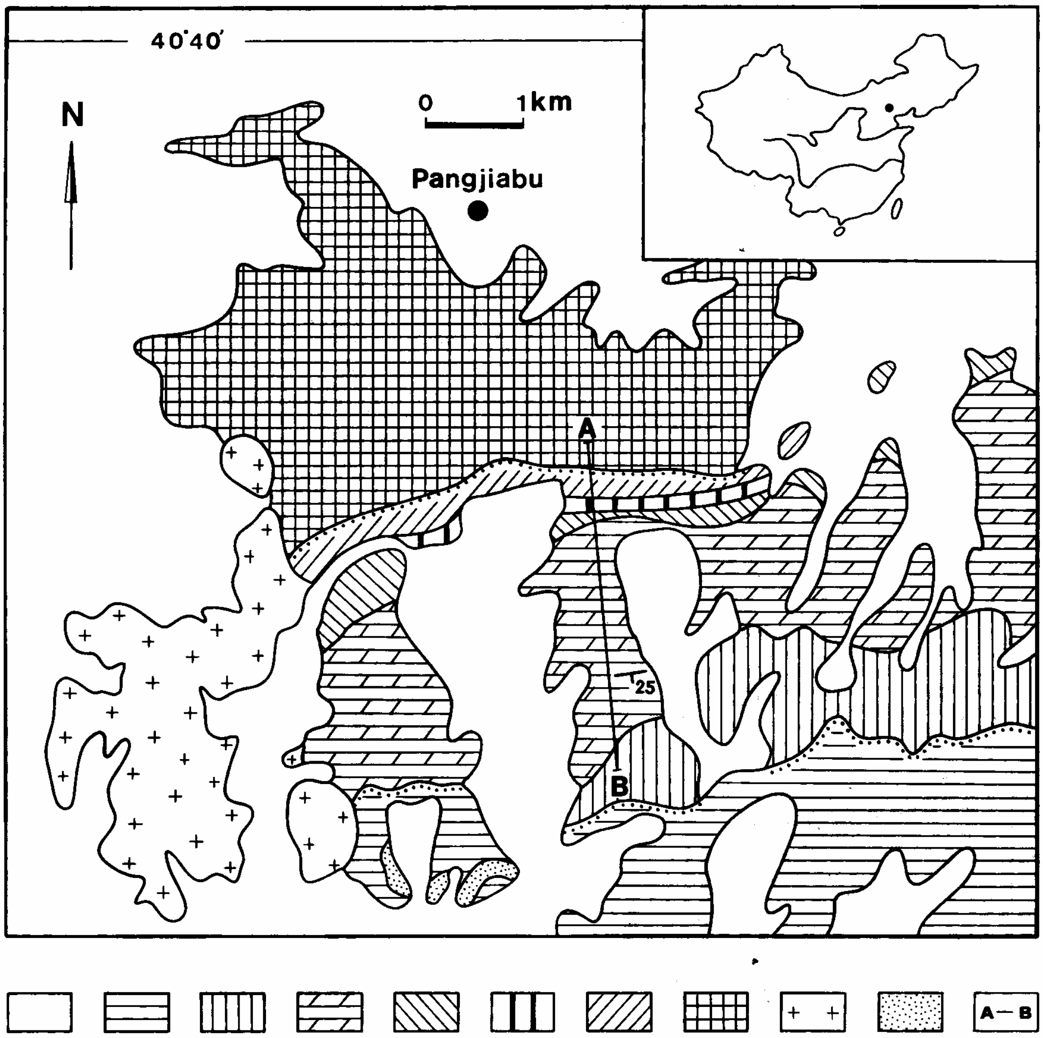
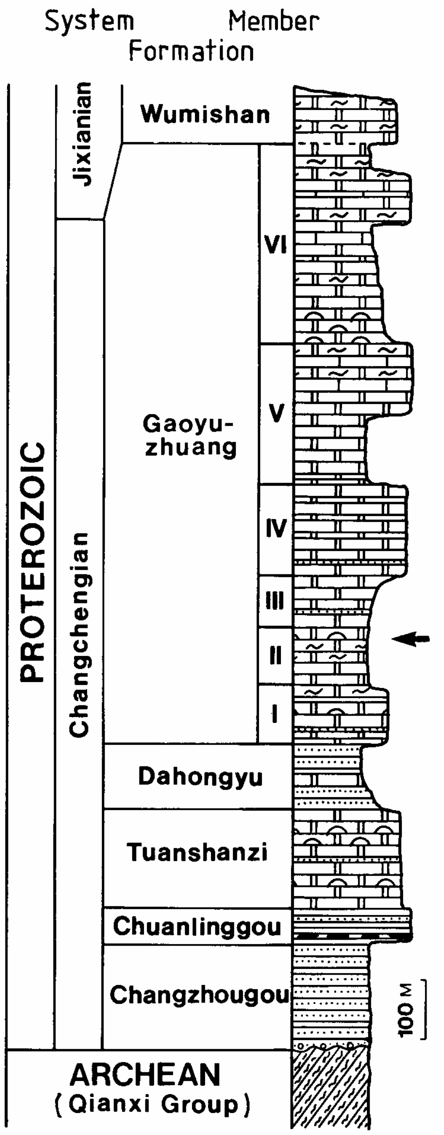


TEXT-FIG. 1. Location and geological map of the Pangjiabu region, Hebei Province, north China. Key: 1, Quaternary; 2, Jurassic; 3, Wumishan Formation; 4, Gaoyuzhuang Formation; 5, Dahongyu and Tuanshanzi Formations; 6, Chuanlinggou Formation; 7, Changzhougou Formation; 8, Archaean (Qianxi Group); 9, Mesozoic granite; 10, orthoclase porphyry; 11, section, summarized in text-fig. 2.

and paraconformably underlies the Wumishan Formation (Jixianian System). The Qianxi Group is composed mainly of granulites, gneisses, and plagioclase-amphibolites. The Wumishan Formation is comprised of cherty dolomites and is the only formation of the Jixianian System which outcrops in this region. The Changchengian System is well developed here, and has been subdivided by many geologists into the five formations described in text-fig. 2.

Radiometric dates for various units of the Changchengian System in the Yanshan Range, North China, have been obtained by the Laboratory of Isotope Geology, Kweiyang Institute of



Gaoyuzhuang Formation (up to 1018 m). Intertidal and subtidal carbonates, mainly grey and dark grey cherty dolomites and stromatolitic dolomites, and minor manganiferous dolomites, siltstones, and silty shales. The formation can be subdivided into six members. Most of the well-preserved spheroidal and filamentous microfossils are found in the black cherts of stromatolitic dolomites which occur in the second member, 100–198 m from the base of the formation (Zhang and Li 1985).

Dahongyu Formation (112 m). Shallow-water, quartzose sandstones, arkosic sandstones, and sandy dolomites, with some brilliant green, K-rich shales.

Tuanshanzi Formation (167 m). Subtidal to supratidal, argillaceous and ferruginous dolomites, sandy dolomites, and dolomitic siltstones and sandstones, with halite casts and stromatolites in upper part.

Chuanlinggou Formation (62 m). Intertidal and subtidal, black and greyish-green silty shales and shales interbedded with siltstones and fine-grained sandstones, with some hematitic iron beds in lower part. The reniform iron ore consists of varied forms of stromatolites (Zhu 1980). Some sphaeromorphic acritarchs have recently been recovered from the shales.

Changzhougou Formation (*c.* 174 m). Shallow-water, intertidal and subtidal, white quartzose sandstones, arenaceous shales, and black shales.

TEXT-FIG. 2. Generalized lithostratigraphic column for section A–B in text-fig. 1, Pangjiabu region, Hebei Province, north China. The arrow indicates the fossiliferous horizon studied.

Geochemistry, Academia Sinica (1977) and the Tianjin Institute of Geology and Mineral Resources (Chen *et al.* 1980). Shale from the Chuanlinggou Formation has yielded a whole-rock Pb–Pb isochron age of 1922 ma, and a U–Pb model age of 1910 ma, while an intrusive porphyritic dyke has yielded phlogopite K–Ar ages of 1817 and 1875 ma. The overlying Tuanshanzi and Dahongyu Formations were dated at 1776 ma (whole-rock U–Pb isochron age), and 1678, 1643, and 1621 ma (K–Ar ages, $\lambda K = 0{\cdot}585 \times 10^{-10} a^{-1}$) respectively. Galena from the Gaoyuzhuang Formation gave whole-rock Pb–Pb isochron ages of 1384, 1434, and 1485 ma. These age determinations indicate that the base of the Changchengian System is approximately 1950 ma and the upper limit of the system is about 1400 ma; these figures have been accepted by most Chinese geologists. The available data, therefore, suggests an age of 1400–1500 ma for the fossiliferous stromatolitic cherts from the Gaoyuzhuang Formation.

MATERIAL AND METHODS

The material studied comes from the top of the second member of the Gaoyuzhuang Formation, 164·6–183·6 m above its base. The unit consists of thin-bedded to medium-bedded, grey and dark grey argillaceous dolomites, cherty dolomites, and stromatolitic dolomites, with some siltstones and silty shales. Well-preserved filamentous and coccoid microfossils are found in black cherts which occur as stromatolitic layers, bands, lenses, or as nodules in dolomites. It is evident that abundant, amorphous organic matter, finely disseminated throughout the silica matrix, makes the chert dark or black in hand specimen. The chert is aphanitic and composed of chalcedony and microcrystalline quartz.

Petrographic thin sections were studied by transmitted light microscopy; most were cut strictly perpendicular to the lamination and 30 μm thick (some thicker sections were cut to avoid damaging the microfossils). The thin sections show the microfossils to be indigenous to the rock, and to have been buried in the surrounding silica matrix during their growth and decay. Some selected rock samples were treated using standard palynological techniques for comparative study.

NOCTIDIURNAL ALGAL GROWTH RHYTHM

Microfabric

The chert layers and lenses preserve a characteristic wave planar microfabric in the stratiform stromatolites. Vertical sections reveal a prominent fine lamination of light, thick, silica-filled layers, generally 350–500 (range 150–600) μm thick, alternating with dark, thinner, algal-rich layers, generally 20–30 (up to 100) μm thick (Pl. 17; text-figs. 3 and 4A–C).The stratiform stromatolites yield abundant filamentous microfossils which are so well preserved that the relationship between micro-organisms and microfabric is revealed. The presence of micro-organisms within a Recent or fossil stromatolite does not necessarily imply any causal relationship with the genesis of the structure (Hofmann 1973), but the filaments described here undoubtedly played an important role in building the microfabric of the stromatolites.

The light layers are composed of anastomosing bundles of filaments, erect or inclined at various angles, which form a three-dimensional reticulated framework. It appears that the filaments are

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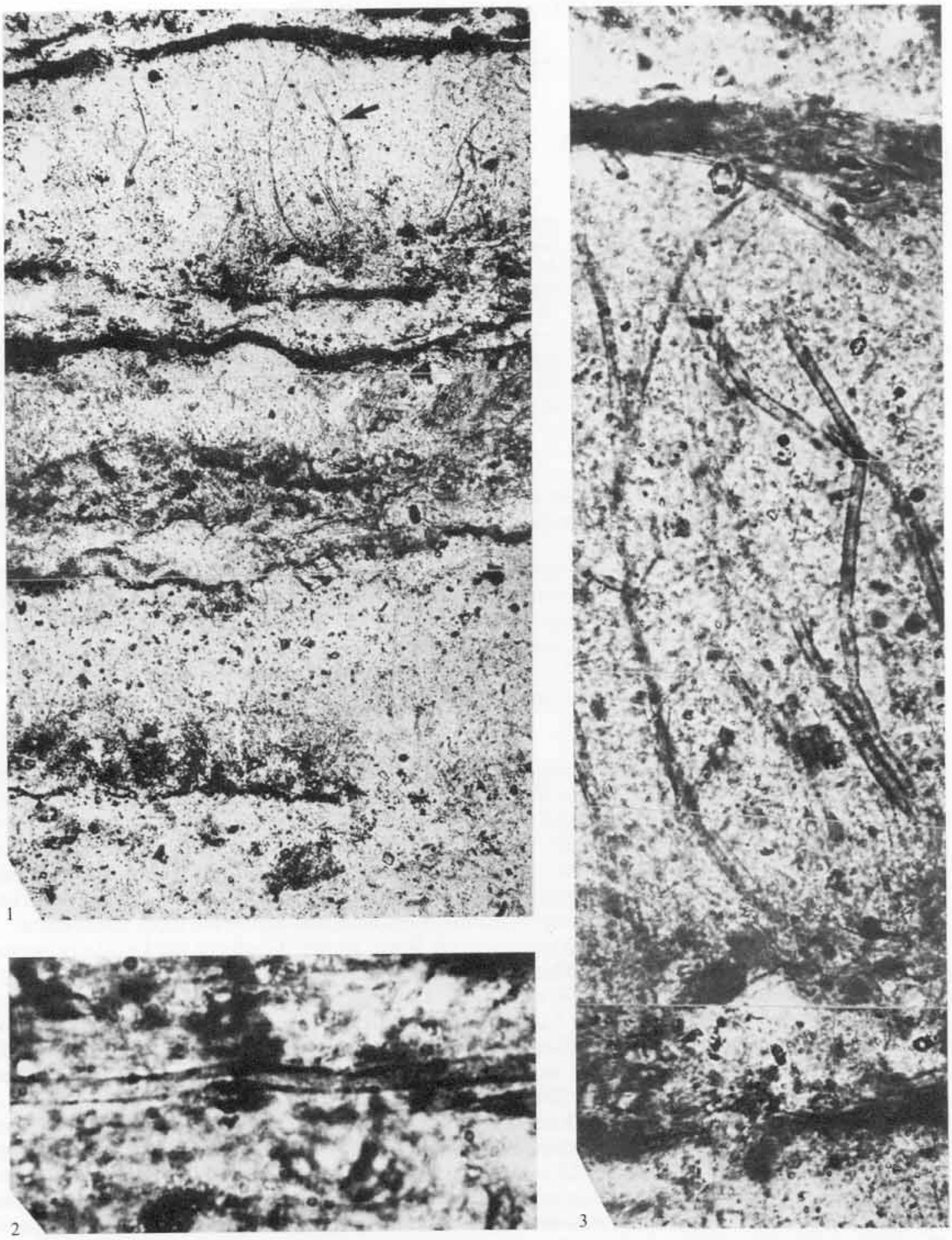
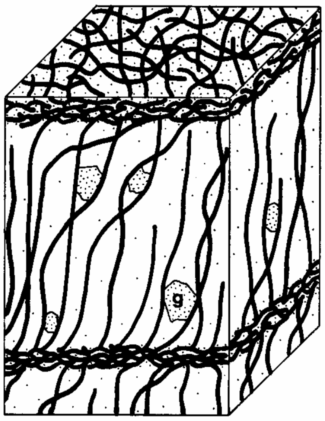
EXPLANATION OF PLATE 17

Figs. 1–3. *Siphonophycus inornatum* Y. Zhang. A probable noctidiurnal growth rhythm of the tubular oscillatoriacean cyanophyte, in stratiform stromatolites of the mid-Proterozoic Gaoyuzhuang Formation, Hebei Province, North China. The thin sections were cut perpendicular to the lamination. 1, Nanjing University Palaeobotanical Collection B8414 (thin section PG79-002), well-preserved biolamination doublets, showing an alternating noctidiurnal sequence of at least four days; each light, thick, silica-filled layer with vertical filaments was formed during daylight, while each dark, thinner, algal-rich layer with horizontal filaments was formed at night, × 110. 2, NUPC B8410 (thin section PG79-001), part of text-fig. 4A, showing detail of prostrate filaments in dark layer, × 800. 3, detail of fig. 1 (arrow), showing transition between day and night-time filament arrangements, × 400.



ZHANG, *Siphonophycus*



TEXT-FIG. 3. Probable noctidiurnal growth rhythm of the tubular oscillatoriacean cyanophyte *Siphonophycus inornatum* Y. Zhang, in stratiform stromatolites of the mid-Proterozoic Gaoyuzhuang Formation, Hebei Province, north China. The vertical section shows a noctidiurnal sequence of two days. The light layer (A) is composed of erect filaments which trapped detrital carbonate grains (g) and records phototactic daytime algal growth. The dark layer (B) is composed of prostrate filaments and was formed at night.

preserved close to their life position since, without mineral support, compaction would have altered their vertical orientation. It thus appears that, in these specific layers, the filaments were supported by a silica matrix during the early stages of diagenesis.

The dark layers consist of prostrate filaments which fuse laterally, are closely crowded into a thin opaque partition, and form a planar reticulated framework. Some of these layers may be completely organic but others often include detrital carbonate particles. At the top of each dark layer the filaments change their growth pattern, turning upwards to assume a vertical position (perpendicular to the lamination) in the overlying light layer before returning to a bedding-parallel orientation again in the next dark layer (Pl. 17, fig. 3; text-fig. 3).

Palaeontology

A notable biological feature of the lamination is that almost monospecific populations, assignable to the tubular oscillatoriacean cyanophyte *Siphonophycus inornatum* Y. Zhang, contribute to microfabric formation. These filamentous algal mats are three-dimensionally preserved *in situ* and their spatial relationships are clearly retained. Not only are the filaments characteristically interwoven along the bedding, but they also exhibit a distinct pattern of horizontally and vertically oriented populations in alternating layers. It is apparent that most Gaoyuzhuang stratiform stromatolites are demonstrably of algal origin; the filaments that built them were also recovered from macerations.

Schopf (1968) erected the genus *Siphonophycus* for large, empty sheaths of the Oscillatoriaceae. There are no distinct morphological differences between *Siphonophycus* Schopf and *Eomycetopsis* Schopf, emend. Knoll and Golubic, 1979, except size. I have recently emended the former genus, and proposed a size limit of not more than 5 μm for average filament diameter to differentiate the two genera (Zhang Zhongying, in press). It should be noted that numerous genera and species are capable of producing extracellular sheaths that, in the fossil record, would be grouped together in the same form genus *Siphonophycus* (see Knoll 1984).

S. inornatum was first described by Zhang Yun (1981) from the same formation (but not the same horizon) and locality as the present material. Filaments of *S. inornatum* are non-septate, unbranched, and tubular, 2·4–8·0 μm in diameter ($\bar{x} = 5{\cdot}1$ μm; $N = 173$) and up to 950 μm long, with a wall thickness of *c.* 0·5–1·0 μm, and a surface texture which is generally smooth but granulate in degraded filaments. This microfossil may represent the external polysaccharide sheaths of *Lyngbya*/*Phormidium*-type blue-greens. As most filaments in the microfabric consist of empty sheaths only, it is reasonable to assume that the trichomes of this micro-organism had a significant gliding motility (trichomes glide out of their sheaths and subsequently produce new sheaths). Some tubular sheaths containing a single degraded trichome were found in the present material.

The mats of *S. inornatum* also contain coccoids: *Palaeoanacystis* Schopf, 1968, *Nanococcus* Oehler, 1977, *Myxococcoides* Schopf, 1968, *Sphaerophycus* Schopf, 1968, and others. Some occur as local populations on a bedding plane, suggesting that they may have been mat dwellers. Others occur as individuals or aggregates more or less randomly distributed throughout the thin section; these may represent allochthonous elements that lived in the water column above the accreting mats.

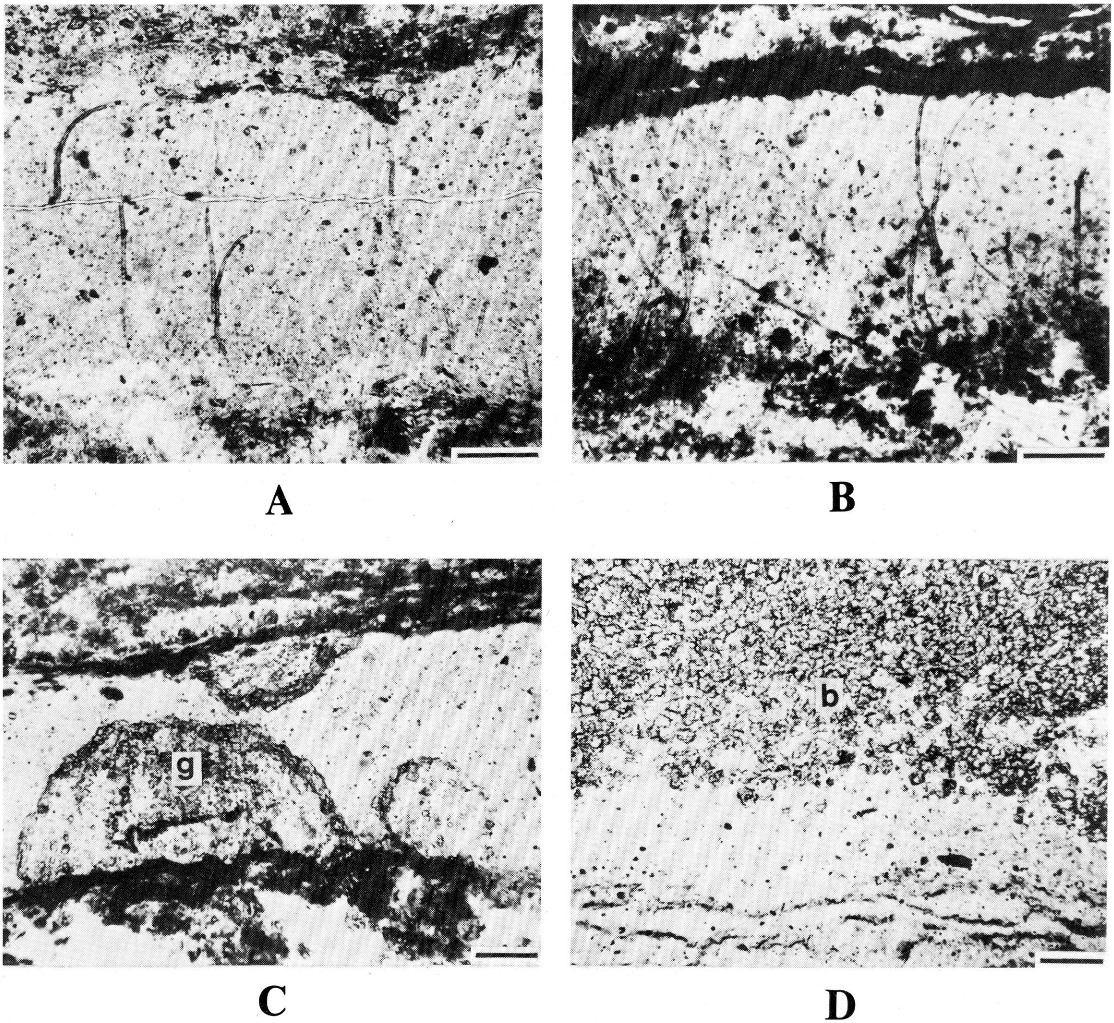
Modern counterpart and interpretation

Extant, non-lithified, finely laminated stromatolitic domes have been repeatedly reported from the western Atlantic ocean and the Caribbean sea (Ginsburg and Lowenstam 1958; Monty 1965, 1967, 1976; Gebelein 1969; Golubic and Focke 1978). Their formation was originally attributed to different micro-organisms: *Symploca laete-viridis* Gomont (Ginsburg and Lowenstam 1958), *Schizothrix calcicola* (Agardh) (Monty 1965, 1967; Gebelein 1969), and *Schizothrix* sp. (Golubic 1973). Later, their high degree of similarity and overlap in morphometric properties led Golubic and Focke (1978) to conclude that these micro-organisms all belonged to the same microbial species, now classified as *Phormidium hendersonii* Howe. This species is motile and characterized by daily movements in accordance with diurnal light variation. Such phototactic movement and subsequent production of a common hard gel can induce an alternate arrangement of vertical and horizontal filaments which, together with entrapped sedimentary particles, produces a primary noctidiurnal lamination. During the day, cell division and vertical movement of the trichome within the ever elongating sheaths are dominant, producing a thick hyaline layer up to 900 μm thick; at night, filaments grow prostrate and at a much slower rate, forming a thin dark layer up to 100 μm thick (Monty 1967, 1976). The gliding motility of its trichomes ensures that 90% of *P. hendersonii* filaments in the interior of stromatolitic domes consist of empty sheaths only (Golubic and Focke 1978).

Similar phototactic responses have also been observed in modern siliceous flat-topped stromatolites built by *P. tenue* var. *granuliferum* Copeland in Yellowstone National Park (Walter *et al.* 1976). Doemel and Brock (1974) reported extant stromatolites built by the photosynthetic filamentous bacterium *Chloroflexus*, in which the bacterium migrates upward at night and grows horizontally during the day—the opposite of *Phormidium*.

Comparison of the stratiform stromatolites from the Gaoyuzhuang Formation (produced by *S. inornatum* mats) with the modern stromatolitic domes from the Caribbean area (produced by *P. hendersonii* mats) demonstrates a great similarity in their microfabric, despite being separated in time by *c.* 1400–1500 ma. Based on its modern counterpart, text-fig. 3 illustrates the possible growth dynamics of *S. inornatum*. One complete lamination of *S. inornatum* is composed of a light, thick, silica-filled layer capped by a dark, thinner, algal-rich layer; each lamination is interpreted as having formed in one day (reflecting a diurnal cyclicity in algal growth, orientation, and movement), the light layers during daylight and the dark layers at night. The daily growth recorded by one lamination was locally as much as 600–700 μm.

During daylight the gliding trichomes of *S. inornatum* moved upward phototactically. They were supported by their sheaths and by bundling of filaments, leading to the formation of a thick layer of erect filaments up to 600 μm thick. A site of some minor relief was probably required for the initiation of algal growth. Under favourable conditions and particularly at a low, more or less constant rate of sedimentation, the rapidly growing mat during daylight would have incorporated sedimentary detrital carbonate as scattered particles in a distinctly hyaline (light), relatively sediment-poor layer (text-fig. 4c). At night, in contrast, *S. inornatum* grew slowly and horizontally to form a thinner, algal-rich (dark) layer made of prostrate filaments. The dark layer is usually only 0·1–0·13 times as thick as the light layer. If sedimentary particles continued to be incorporated at the same rate, the density of particles accumulated during the night within the dark layer would have been 8–10 times higher, and the dark layer would have become easily loaded to capacity with detritus. The overnight prostrate sheets developed even when sedimentation ceased altogether; in this case they appear in thin section as a thin, dark line. With the resumption of growth the following day the trichomes must have glided out of their sheaths, turned upwards to a vertical orientation (perpendicular to the bedding), and trapped sedimentary grains, thereby producing a new light layer.



TEXT-FIG. 4. A laminated organosedimentary structure produced by the tubular oscillatoriacean cyanophyte *Siphonophycus inornatum* Y. Zhang, in stratiform stromatolites of the mid-Proterozoic Gaoyuzhuang Formation, Hebei Province, north China. Bar scale is 100 μm long; all vertical thin sections. A, C, Nanjing University Palaeobotanical Collection B8410 (thin section PG79-001); B, NUPC B8412 (thin section PG79-076); D, NUPC B8414 (thin section PG79-002). A, B, horizontally and vertically orientated filaments in alternating layers; the light layers are composed of erect filaments and interpreted as recording phototactic daytime algal growth, whereas the dark ones are composed of prostrate filaments and reflect nocturnal growth. C, part of light layer in A, showing entrapped detrital carbonate grains (g). D, light layer (about 4 mm below Pl. 17, fig. 1) swamped by intensive sedimentation; basic biolamination no longer distinct, and a massive boundstone (b) was formed.

DISCUSSION AND SUMMARY

Students of ancient stromatolites have fallen into two broad 'schools' during the last thirty years: the 'biostratigraphical school' considers fossil stromatolites to be biogenic entities, many of which have been used as time-stratigraphical tools; the 'palaeoecological school' considers fossil stromatolites to be sensitive environmental indicators. Recent studies of the microbial composition of modern algal mats call for a more integrated approach, taking both biotic and environmental interpretations into consideration. According to Golubic and Focke (1978), populations of a single algal species living under different conditions (ranging from subtidal to intertidal) always produce remarkably similar stromatolites. Sedimentological studies indicate that the Gaoyuzhuang Formation consists mainly of cherty dolomites and stromatolitic dolomites formed in intertidal and subtidal environments. The associated stratiform stromatolites are laminated organosedimentary structures produced by the active, tubular oscillatoriacean form taxon *S. inornatum*, thus supporting the interpretation of biological control for stromatolites, irrespective of differences in environmental conditions within the range of their distribution. However, the optimum habitat for *S. inornatum* mats may have been shallow, intertidal, hypersaline lagoons in a warm climate, with some aerial exposure during the tidal cycle.

Diurnal light variation appears to have been responsible for the microfabric of the *S. inornatum* mats described above. These mats retain within their microfabric a record of rhythmic growth, movement, and the particle-trapping behaviour of the filaments that built the stratiform stromatolites. The distinctive orientation of *S. inornatum* filaments also demonstrates that, at least in some areas of the mid-Proterozoic Gaoyuzhuang Sea, the sheaths of *S. inornatum* were autochthonous; thus, this micro-organism occurred as a primary mat builder. The evidence suggests that the biolaminations built by *S. inornatum* record a probable solar cyclicity 1400–1500 ma ago. This kind of noctidiurnal rhythm in the orientation and growth dynamics of algal filaments must have existed in the early history of the Earth, and similar microfabrics are to be expected in other Precambrian stromatolites. Knoll (1981) mentioned that some *Eomycetopsis robusta* mats preserved in silicified, flat-laminated, microbial stromatolites from the Ross River (late Precambrian, *c.* 740–950 ma) occasionally display a distinct microfabric in which members of the population are orientated parallel to the bedding plane in one lamina, turn upward to a vertical position in the overlying band, and then return to a bedding-parallel orientation. This example probably represents a phototactic response by the micro-organism involved.

'Ideal' biolamination doublets are not always well developed. Often the doublets appear in thin sections to be somewhat erratic and incomplete. Since the biolamination originated from the combined effects of algal growth and sedimentation, its development depended on a harmonious balance between the algal growth rate and the quantity of available sedimentary particles: at high sedimentation rates the biolamination was obliterated by oversedimentation and a massive boundstone was formed (text-fig. 4D); where sediment supply was low or zero the growth of a purely algal mat prevented biolamination. The rates of both processes vary through time and space, not only between different algal populations, but also between different portions of one population, making the resulting biolamination more complex.

Several biological, geochemical, physical, and sedimentological factors can influence algal growth and sedimentation rate, e.g. invasion of the mats by other micro-organisms, changes in intensity of incident sunlight, the destructive effects of strong wave surge, heavy rain, and swift currents, the slowing down of algal growth rate during periods of drought or when higher salinities prevailed, and the destruction of laminations by abrasion in areas of very rapid sediment movement. From observations on the algal growth of Recent stromatolites (Monty 1967, 1976; Walter *et al.* 1976), it can be predicted that *S. inornatum* had periods of rapid algal growth, periods when it slowed down, and even periods when the mats stopped growing for several days, during which time nothing was added to the biolamination.

Post-depositional changes must also be considered. Prior to silicification, the algal mats would have undergone structural degradation, compaction, and diagenetic destruction, thereby obscuring the biolamination and altering the vertical orientation pattern of the component filaments. A biolamination is only well-preserved in zones where silicification took place during the early stages of diagenesis.

A continuous sequence of several tens of biolamination doublets has not been found in thin sections of the present material, for reasons outlined above. It is therefore impossible to determine the complete age of the algal microfabric by counting biolamination doublets in thin sections. Such doublets, however, strongly favour the existence of an ancient noctidiurnal growth rhythm in *S. inornatum*.

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ZHANG ZHONGYING

Department of Geology
Nanjing University
Nanjing
People's Republic of China

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